ABSORPTION AND SCATTERING OF HETEROGENEOUS X-RAYS BY ELEMENTS OF LOW ATOMIC NUMBER.

BY

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INTRODUCTION.

Experimental investigation of the phenomena associated with the interaction of matter with radiation are extremely important and interesting, as such investigations throw considerable light on the nature of matter and that of radiation.

For example, the discovery of the characteristic X-rays emitted by various elements when suitably excited, coupled with the theoretical background of the Bohr-Rutherford model of an atom has presented, at least approximately, a very pleasant and relatively simple picture of the structure of atoms. Also, Sir William Bragg's discovery of the diffraction of X-rays by crystals has yielded very considerable knowledge of atomic arrangements in the molecules making up the crystal.

At present, atomic, as well as molecular structure investigations by means of the interaction of X-rays with matter, have reached the status of a refined science. It is, therefore, only natural to expect that similar phenomena would be helpful in giving us some conception of the nature of the X-rays themselves.

This aspect of the problem, however, has so far proved to be very difficult, and no simple satisfactory conception of the nature of radiation could be evolved from experiment. The principal difficulty lies in the fact that some of the experimental results such as the photoelectric effect, the excitation of the characteristic radiations, the presence of recoil electrons in a C.T.R. Wilson's cloud chamber, the

limiting wavelength of the 'general' radiation in an X-ray tube by the application of a given potential difference and the 'softening' of the rays scattered from elements of low atomic number, and various other phenomena seem to require a corpuscular conception of radiation and give rise to the Photon or Quantum Theory of radiation which is characterised by Einstein's equation.

Energy of a photon = $h\nu$

and in the first instance requires the Principles of Conservation of Energy and of Momentum, although in some aspects these Principles take on rather strange forms, in particular, a state of negative kinetic energy of an electron appears to be permissible, and in fact, essential for the explanation of the well established phenomena of 'cold emission' 'tunnel effect' and electron-positron pair production by very high frequency γ and cosmic rays.

On the other hand, however, some experiments such as Barkla's discovery of the complete polarisation of X-rays scattered at 90° to the incident radiation, the partial polarisation of the rays emitted from an X-ray tube, the diffraction of X-rays by crystals and very fine gratings, and even perhaps the actual distribution of the photo electrons emitted from matter, and the presence of the 'Unmodified' Scattered rays and various other phenomena seem to require an electromagnetic wave conception of X-rays and lead to what is now usually termed the 'classical' theory.

It is thus seen that we are unable to explain all the experimental results by any definite conception of the nature of radiation, and for the present must satisfy ourselves by

interpreting some of the results in terms of the Photon Theory and others in terms of the Classical Electro-Magnetic wave theory. This, of course, is a very unsatisfactory state of affairs and it is hoped that by further careful experimental research we may be able to discover some method of accounting for all the experimental results by a single well defined theory of radiation.

It seems probable that one of the best aspects of the matter-radiation interactions to investigate, with the above object in mind, is that branch of phenomena associated with the process of scattering of radiation by matter, and in particular, to simplify matters, the phenomena associated with the scattering of radiation by free or loosely bound electrons, as in this case considerations of the atomic structure can, at least to a first approximation, be eliminated.

With this object in view, C.G. Barkla initiated a series of experiments in which certain aspects of Scattering and Absorption of X-rays by matter were investigated. Under his guidance, some very interesting results have been obtained during the last few years and have been published by him and his assistants under the various headings involving the 'J' Phenomena.

The work reported in this paper is based on some further experiments made in connection with the J-Phenomena and some of the results of previous workers have been confirmed and the range and nature of the experiments have been considerably extended.

Before, however, describing and discussing these

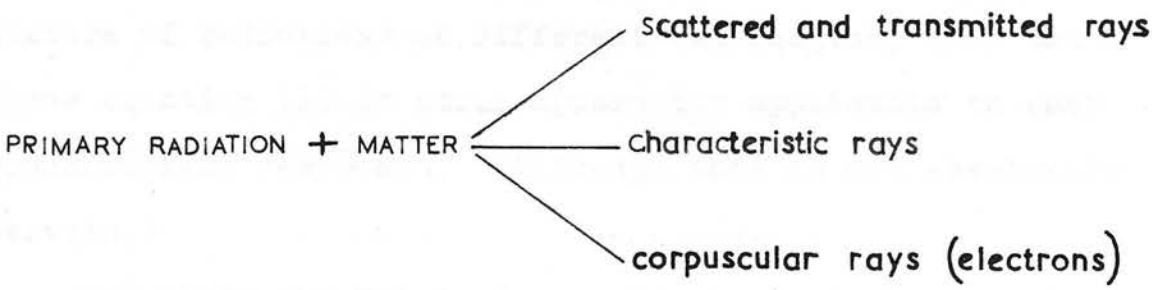
experiments, it is desirable to give a brief summary of our present knowledge of the scattering of X-radiation.

INTRODUCTORY DISCUSSION.

In general, when X-rays pass through matter, part of the incident radiation is scattered in all directions, and part is absorbed by the matter, which in its turn is found to emit characteristic radiations, which are principally dependent on the atomic structure of the element or elements constituting the matter.

The irradiated matter is also found to emit corpuscular radiations consisting entirely of photo- and recoil electrons.

The interaction of X-radiation with matter may consequently be conveniently represented in diagramatic form thus:



All the radiations emitted by irradiated matter, grouped together, are usually referred to as the Secondary Radiations, and the incident radiation as the Primary radiation.

We will now briefly consider the properties of each type of secondary radiation separately.

I. THE TRANSMITTED RADIATION.

If the Primary radiation is homogeneous, i.e. monochromatic, then the transmitted radiation is found to be apparently identical with it in every respect, except in

intensity, which is invariably less in the transmitted beam than in the incident beam. The intensity I_x of a homogeneous radiation emerging through a sheet of matter of thickness x is given by the expression

$$I_x = I_0 e^{-\mu x} \qquad (1)$$

where I_0 is the intensity of the incident radiation defined as the energy passing per second through unit area placed normal to the beam, and μ is the linear absorption coefficient of the incident radiation in the matter.

This linear absorption coefficient is defined as the fractional reduction in the intensity of the beam by unit path in the absorbing substance. If, on the other hand, the Primary radiation is heterogeneous, i.e. consists of a mixture of radiations of different wavelengths, then the above equation (1) is still apparently applicable to each monochromatic component. (Although this is not absolutely certain.)

And since the value of μ for a given absorber is nearly proportional to λ^3, it follows that the intensities of the components of the incident radiation having longer wavelengths will be reduced, on passing through the absorber, much more than the intensities of the components having shorter wavelengths. Thus the transmitted radiation will, on the whole, contain a greater proportion of the shorter wavelengths than the incident radiation and will therefore be rendered more penetrating or 'hardened'.

In other words, heterogeneous radiation filtering through matter is 'hardened', and the greater the thickness of the filter, the smaller the intensity of the transmitted

radiation, but the penetrability or hardness of the radiation is increased.

In dealing with heterogeneous radiations we cannot, of course, specify a definite linear absorption coefficient, but we can define an 'Average Linear Absorption Coefficient' in terms of the thickness of the filter of a given substance which will cut down the intensity of the transmitted radiation by a half.

$$\frac{1}{2} I_o = I_o e^{-\mu' x'}$$

$$\therefore \quad \mu' = \frac{\log_e 2}{x'} \quad - \quad - \quad - \qquad (2)$$

This conventional definition of the 'linear' absorption coefficient of heterogeneous radiation is a very convenient and reliable one, and gives us a relatively simple way of comparing different heterogeneous radiations.

The linear absorption coefficient is, of course, dependent on the physical state of the absorber, but if we divide the linear coefficient of absorption by the density of the absorber, we get what is called the 'mass absorption coefficient' and this is found to be independent of the physical state of the absorber, provided the absorber behaves as an amorphous body and not showing any marked crystal diffraction effects.

In the work presented in this thesis we shall generally refer to the mass absorption coefficient of any radiation as the one computed from the thickness of Aluminium required to

decrease intensity of the transmitted radiation by precisely 50%.

In addition to the purely transmitted beam, we also have a superposition of a relatively small amount of 'scattered' radiation, i.e. radiation which is scattered by the absorber in the forward direction.

The intensity of this scattered radiation is very small indeed compared with the 'transmitted radiation'; we can, therefore, consider the radiation emerging from the absorber, in the direction of the incident beam, to be simply the transmitted beam. This point will be returned to in the next section.

THE SCATTERED RADIATION.

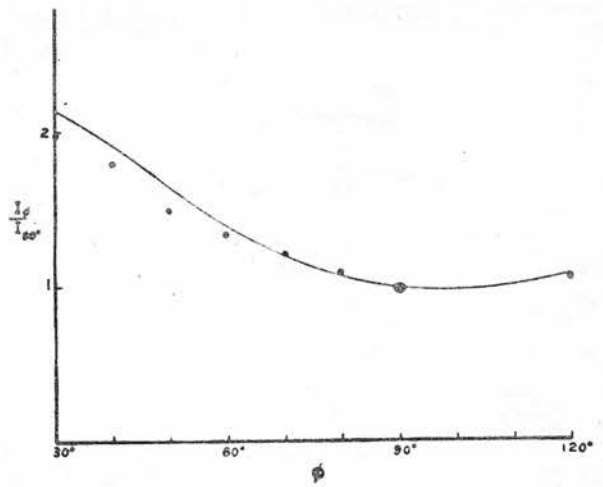
The scattered radiation emerges in all directions and, on the classical theory, (in which the electron is made to vibrate by an electromagnetic wave as the latter passes it), the intensity of the radiation scattered in a direction making an angle ϕ with the incident radiation is given by the expression

$$I_{\phi} = I_{\pi/2}\left(1 + \cos^2\phi\right) \qquad (3)$$

where $I_{\pi/2}$ is the intensity of the radiation scattered at 90° to the incident radiation.

Equation (3) above only shows the relative intensities scattered in the various directions, and is shown by the dotted curve in Fig. 2. The formula only holds for unpolarised radiation, and on the basis of the classical theory

is supposed to be independent of the wavelength of the incident radiation.



. Scattering from paraffin. Curve from Dirac theory, dots are values from experiment.

fig 1.

The dotted curve in Fig. 1 shows the experimental results for the intensity distribution of heterogeneous radiation (white, or general radiation obtained from a Tungsten anticathode Coolidge tube operated at a potential difference of 80 Kv., and filtered through ·244 mm. Al) scattered from a thin slab of Paraffin Wax, as obtained by Allen Coven(1).

The writer would, however, like to point out that a direct comparison of Coven's experimental results with the classical theory cannot be made owing to the fact that Coven did not take into account the partial polarisation of the general radiation emitted by the tube. In fact, Coven's result is only given here because it represents the intensity distribution of heterogeneous radiation of a type which is typical of the radiations used throughout this work by the present writer, and may therefore be interesting.

The comparison between the classical theoretical and

experimental angular intensity distribution curves are best shown in Fig. 2, where the black full line represents Barkla's results for scattering of fairly long wavelength radiation by Carbon and the full red line represents Crowther's results for scattering from Aluminium.

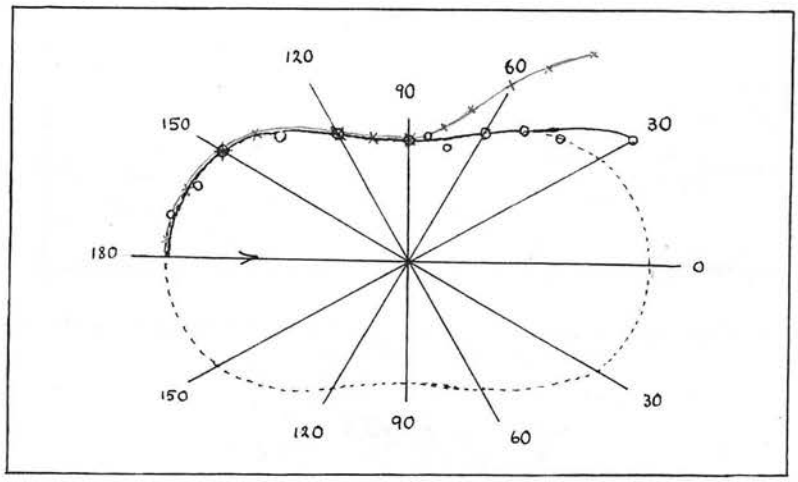


Fig 2.

It will be seen that the intensity distribution of the scattered radiation for these wavelengths is in quite good agreement with the theoretical curve for angles between 60 and about 180°, but below 60° there is generally an excess of scattered radiation. This effect has been accounted for quite satisfactorily in terms of the classical theory by assuming that at small angles the electrons scatter in groups rather than individually as postulated by the original Thomson theory.

The effect of the wavelength of the incident radiation on the angular distribution of intensity of the scattered radiation is well shown in Figs. 3 and 4.

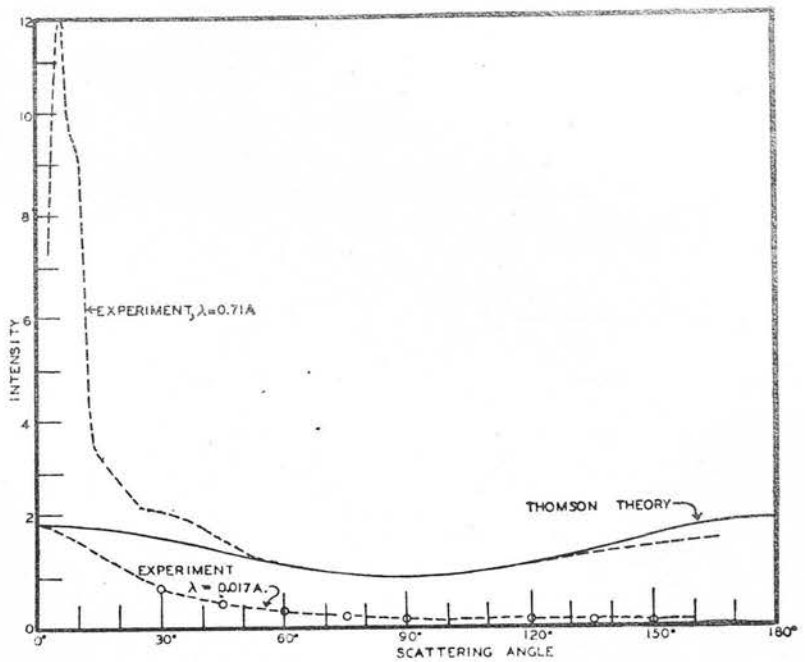


FIG. III—■ Scattered x-rays are more intense at small than at large angles. Upper curve, mesitylene (liquid), lower curve, iron.

fig. 3

In Fig. 3 the intensity of the radiation scattered in the forward direction (in the case of longer wavelength radiation scattered by a liquid), as reported by Hewlett, shows a sudden marked decrease in the intensity at small angles of scattering, and in fact Hewlett[2] considers the intensity of the scattered radiation in the direction of the incident beam to be zero, even with solid scatterers. In view of this effect we are still further justified in considering the transmitted beam to be a 'truly transmitted' and free of any superposition of scattered radiation.

The maximum intensity of radiation scattered at small angles has been confirmed photographically by KEESOM and SMEDT, and has also been satisfactorily explained by interference phenomena arising from group rather than individual scattering centres.

The slight deficiency in the intensity of the radiation scattered backwards could not, however, be accounted for on the classical electromagnetic wave theory.

This deficiency in scattering at about 180° was found to be more marked when the incident radiation was of short wavelength than when it was of longer wavelength.

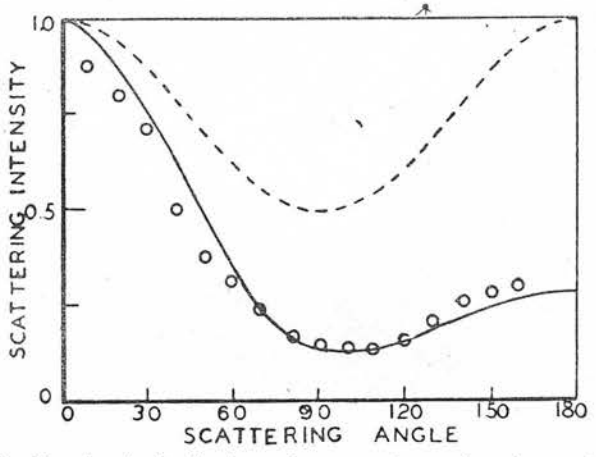


FIG. [redacted]. Directional distribution of x-rays of wave length 0.14 Å, scattered by water as compared with Breit-Dirac theory (solid curve) and classical theory (broken curve), according to Friedrich and Goldhaber.

fig. 4.

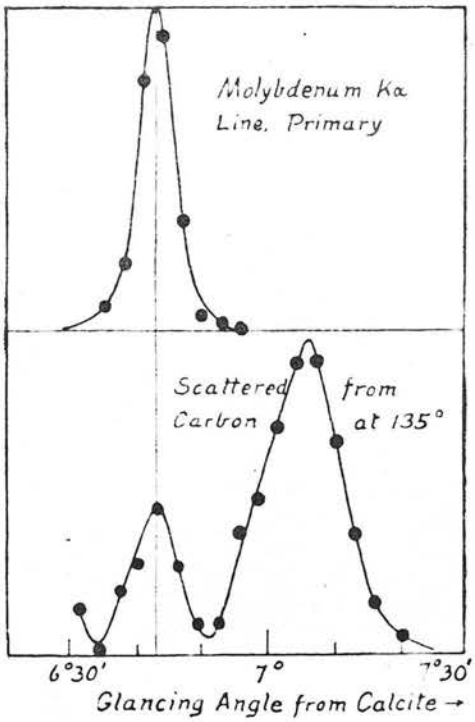
The deficiency of the radiation scattered at large angles has been accounted for by Breit-Dirac and Klein-Nishina, in terms of the corpuscular or photon theory of radiation.

In Fig. 4, we compare the experimental intensity distribution with the theoretical curve of Breit-Dirac and the classical curve shown by the broken line.

Experimental work on the angular intensity distribution of scattered γ rays by Chao[3] seems to be in very good agreement with the values predicted by the Klein-Nishina[4] formula:

$$I_\theta = I_0 \frac{e^4}{2m^2c^4} \frac{1 + \cos^2\theta}{\{1 + a(1 - \cos\theta)\}^3} \left\{ 1 + \frac{\pi^2 (1 - \cos\theta)^2}{(1 + \cos\theta)(1 + a[1 - \cos\theta])} \right\} \quad \cdots (4).$$

where $a = \frac{h\nu}{mc^2}$


Molybdenum Kα
Line. Primary
Scattered from
Carbon at 135°
6°30'
7°
7°30'
Glancing Angle from Calcite →

NATURE OF THE SCATTERED RADIATION.

With certain exceptions reported by Barkla, the scattered radiation was generally found to be 'softer', i.e. more absorbable than the incident or transmitted radiations, even when the latter was monochromatic or homogeneous.

It thus seemed that in the process of scattering, the incident radiation underwent some definite transformation. Compton, using a primary beam of monochromatic X-radiation and a crystal spectrometer, examined the spectrum of the radiation scattered in different directions by various scatterers and found the scattered radiation to consist of two distinct 'lines' in the spectrum. One of these wavelengths was identical with that of the incident radiation and was consequently called the 'Unmodified Scattered Radiation', whereas the other line was produced by a slightly longer wavelength radiation and was therefore due to a 'Modified Scattered Radiation'.

Compton also put forward a theoretical explanation of the production of the modified scattered radiation in terms of the photon theory, and obtained the expression:

$$\delta\lambda = \frac{2h}{mc} \sin^2 \frac{\phi}{2} \qquad (5)$$

giving the relationship between the change in wavelength of

the modified scattered radiation and the angle of scattering, it is seen that according to this theory, the change in wavelength is independent of the wavelength of the incident radiation and the effect is therefore more marked in the case of scattering of high frequency X-radiation and, in particular, in the case of scattering of γ-rays. This effect has been confirmed for γ-rays.

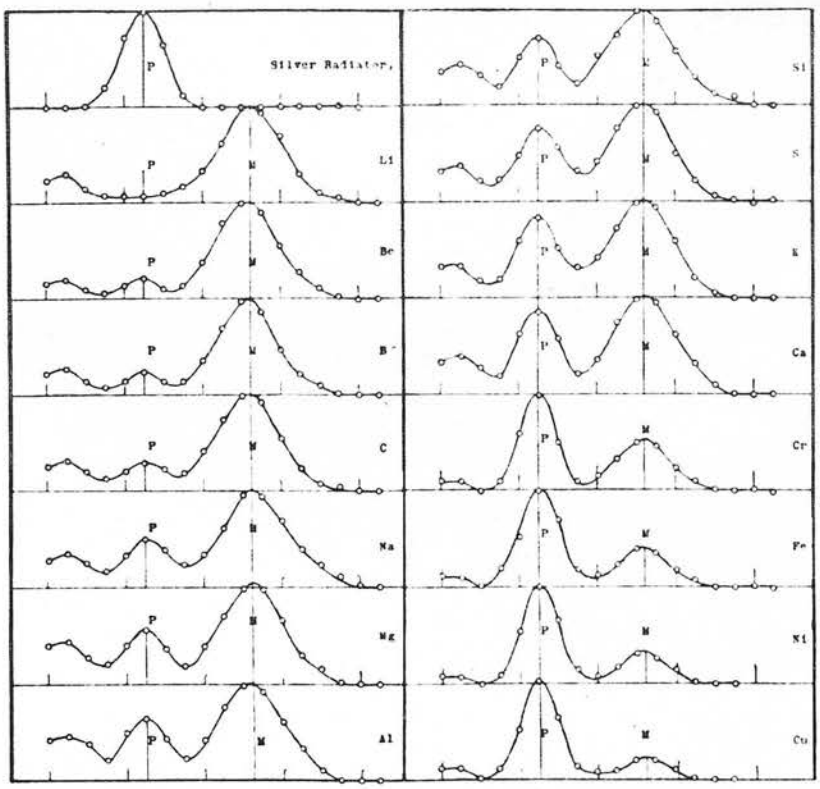


FIG. [redacted] Spectra of silver $K\alpha$ line scattered by different elements, showing the increase in prominence of the unmodified line with increasing atomic number. (Woo.) 5

fig 5.

In Fig. 5 the spectrum of the incident radiation (Ag K_α) is shown at the top, and is compared with the spectra of the radiation scattered by different elements at 135° to the incident radiation. It will be noticed that in every case the change in wavelength of the modified radiation is the same, i.e. the change is independent of the atomic number of the scatterer, but the relative intensities of the modified and unmodified scattered radiations do depend on the atomic number;

in fact, with a Lithium scatterer the whole of the scattered radiation appears to be modified for this angle, whereas with a silver scatterer the whole of the scattered radiation appears to be unmodified.

The experimental determination of the ratio of the intensities of the modified to the unmodified scattered radiations has been carried out by Woo[6] and his results are shown in TABLE I.

rays scattered at 120°					
Radiator	At. No.	Int. Ratio $\frac{\text{Mod}}{\text{Unmod.}}$	RADIATOR	ATOMIC No.	$\frac{I \text{ MOD.}}{I \text{ UNMOD.}}$
Li	3		S	16	1·91
Be	4	8·72	K	19	1·72
B	5	7·02	Ca	20	1·71
C	6	5·48	Cr	24	0·75
Na	11	3·04	Fe	26	0·51
Mg	12	2·78	Ni	28	0·40
Al	13	2·61	Cu	29	0·21
Si	14	2·33	Ag		

Various theoretical formulations of this dependence of the ratio of the modified to the unmodified scattered radiations on the atomic number of the scatterer have been produced by C. WENTZEL[7] I. WALLER[8] AND D. R. HARTREE[9] but the agreement with Woo's results were only approximate. The writer finds, however, that if the ratios of the intensities of the modified to unmodified radiations scattered by different elements (as given in Woo's table above) are plotted against

the reciprocal of the atomic number of the scatterer, the resulting curve is practically a straight line, Fig. 6, showing empirically that the relationship between the ratio of modified to unmodified scattering and the atomic number of the scatterer is given by:

$$\frac{I_{MOD.}}{I_{UNMOD.}} = \alpha \frac{1}{N} + \beta \qquad (6)$$

where α and β are constants depending on the wave length and angle used, and where N is the atomic number of the scatterer, and the expression appears to be valid for the range of elements from Be to Ca.

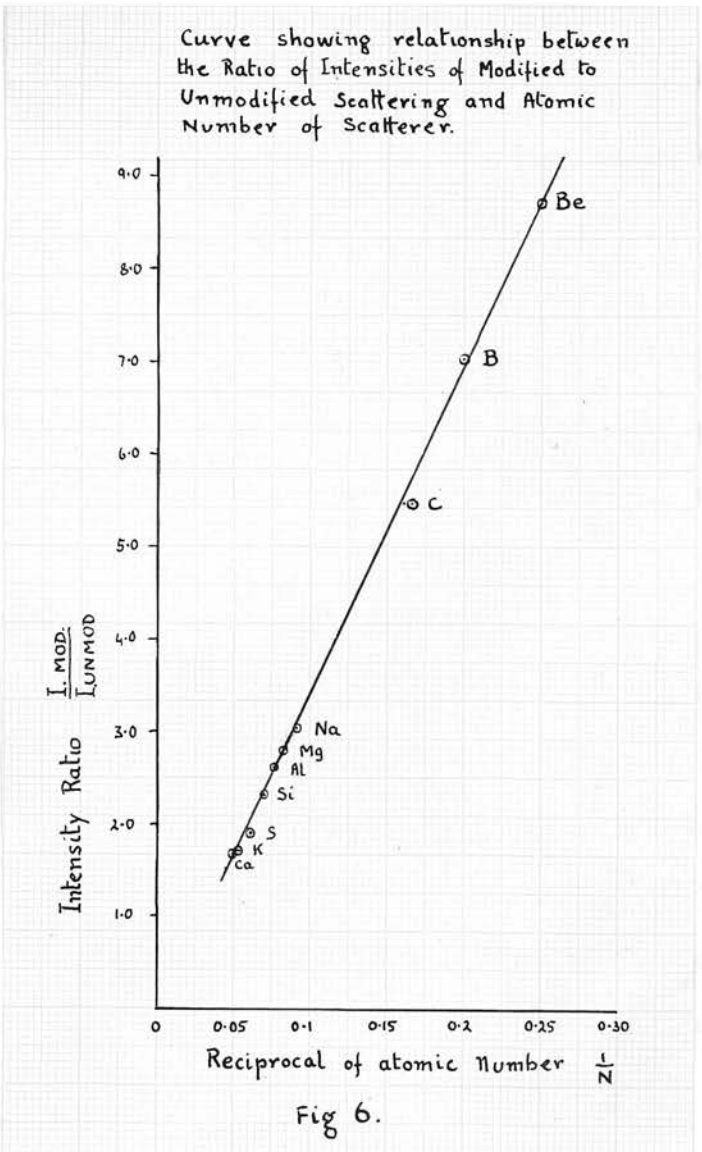


Fig 6.

It is important to stress, however, that this particular variation of the ratio of the intensities of the modified to unmodified scattered radiations with the atomic number of the scatterer, does not, as far as experimental evidence at present shows, hold for other angles of scattering.

In fact, P.A. Ross's[10] experimental work gave the results shown in TABLE II,

TABLE II

Ratio of Intensity of Modified to Unmodified Lines

Scatterer	Incident Radiation	Scattering Angle	Ratio of Inten. $\frac{\text{Mod}}{\text{Unmod.}}$
Graphite	$M_o\ K_\alpha$	30°	0·2
Graphite	$M_o\ K_\alpha$	60°	0·95
Graphite	$M_o\ K_\alpha$	90°	1·7
Aluminium	$M_o\ K_\alpha$	90°	0·7
Aluminium	$M_o\ K_\beta$	90°	1·0

and apparently shows that the intensity of the modified scattered radiation relative to the unmodified scattered radiation increases as the angle increases from 30° to 90°.

Unfortunately, however, Ross does not give any details of the technique he used and corrections applied, so that the validity of the above results is not absolutely certain, and are generally in agreement with the requirements of Quantum Theory. It would therefore be very desirable to investigate the dependence of the ratio of the intensities of the modified to unmodified scattering experimentally, as this type of

investigation would undoubtedly throw considerable light on the mechanism producing modified scattering.

P.A. Ross,[11] M. de Broglie, Allison and Duane, and Compton all agree in stating that the relative intensity of the modified to unmodified scattering is much greater when Tungsten K radiation is scattered than when Molybdenum K_a radiation is used. In fact, it seems that the higher the frequency of the incident radiation, the greater the relative intensity of the modified scattered radiation. In the case of Cu K radiation scattered from Al, no modified line was found.

Unfortunately, the exact or even approximate dependence of the intensity of the modified scattered radiation on the frequency of the incident radiation does not seem to have been systematically and quantitatively investigated experimentally. This type of investigation would also be very desirable and it seems to the writer would be of considerable importance when scattering heterogeneous radiation. We will return to this point later when discussing the results of the experiments reported in this work.

Experimental work by Barkla,[12] Compton and Hagenow[13] showed that all the radiation scattered at 90° to the incident radiation was completely plane polarised, that is, <u>both</u> the modified and unmodified scattered radiations were $100^{\circ}/_{0}$ plane polarised, the plane of polarisation being in accordance with that predicted by classical electromagnetic theory.

The polarisation of the radiation scattered at 90° receives a very concise and simple explanation in terms of the classical theory, but no satisfactory explanation of polarisation in terms of the quantum theory of radiation has

been produced as yet, although attempts have been made to account for it in terms of the neutrino theory of radiation where a photon was supposed to be made up of a neutrino and an antineutrino and the polarisation of the radiation was interpreted in terms of certain orientations of the spin axis of these particles. This conception, however, was purely theoretical and even so is not, at present, regarded seriously.

Barkla also showed that the general radiation emitted by an X-ray tube was partially polarised; it further appeared that the radiation at or near the short wave-length limit of the general radiation was completely plane polarised, again in accordance with classical theory where an electro-magnetic wave is produced by the sudden stoppage of an electron.

Barkla also found that the total percentage of polarisation defined as:

$$\frac{\text{Intensity of a polarised component} \times 100}{\text{total intensity}}$$

decreased with increase of the Kilo-voltage applied across the tube.

In experiments on the scattering of heterogeneous radiation, and in particular on the scattering of the general radiation, due consideration must be given to the effects produced by this partial polarisation of the incident radiation.

THE SCATTERING COEFFICIENT

As already mentioned, when X-radiation falls on matter, part of this radiation is scattered in all directions, and in consequence of this, the intensity of the transmitted beam will be less than that of the incident beam. (We neglect for the moment the absorption due to the production of characteristic radiation and photo electrons.)

For homogeneous radiation it is found that the intensity I_x of the radiation transmitted through a thickness x of matter is given by:

$$I_x = I_o e^{-\sigma x} \qquad (7)$$

where σ is the scattering coefficient of the given material and I_o the intensity of the incident beam.

The linear scattering coefficient σ is defined as the fractional reduction in the intensity of the beam by unit path in the scattering substance, and this quantity is also dependent on the physical state of the scatterer, but the quantity obtained by dividing the scattering coefficient by the density of the scatterer appears to be independent of the physical state of the scatterer, and is called the mass scattering coefficient of the given material.

It is generally believed that the incident radiation is scattered by the electrons in the atoms individually, so that by calculating the number of electrons in a cubic centimetre of the scatterer we can find the scattering coefficient per electron, on the classical theory, this electronic scattering coefficient is given by the formula

$$\sigma_e = \frac{8\pi}{3} \frac{e^4}{m^2 c^4} \qquad (8)$$

where **e** is the electronic charge in E.S.U.

m is the mass of the electron in gms.

and **c** is the velocity of light in cms/sec.

Substituting the modern values for these constants, it was found that the electronic scattering coefficient turned out to be 666×10^{-27} and had the dimensions of area.

$$\sigma \text{ (classical)} = 666 \times 10^{-27} \text{ cms}^2.$$

In the above expression, (formula **8**) it is seen that the electronic scattering coefficient appears to be independent of the wavelength of the incident radiation. (The writer's views on this point will be discussed more fully later in the Discussion of Results).

Experimental measurements of the mass scattering coefficient and hence also those of the electronic scattering coefficient definitely showed, however, that the coefficient was a definite function of the wavelength of the incident radiation and tended to decrease rapidly, as the wavelength of the incident radiation decreased. This variation of the electronic scattering coefficient with the wavelength of the incident radiation is well illustrated in the experimental results obtained by T. Cuykendall[14] for scattering from Carbon, shown in Fig. 7.

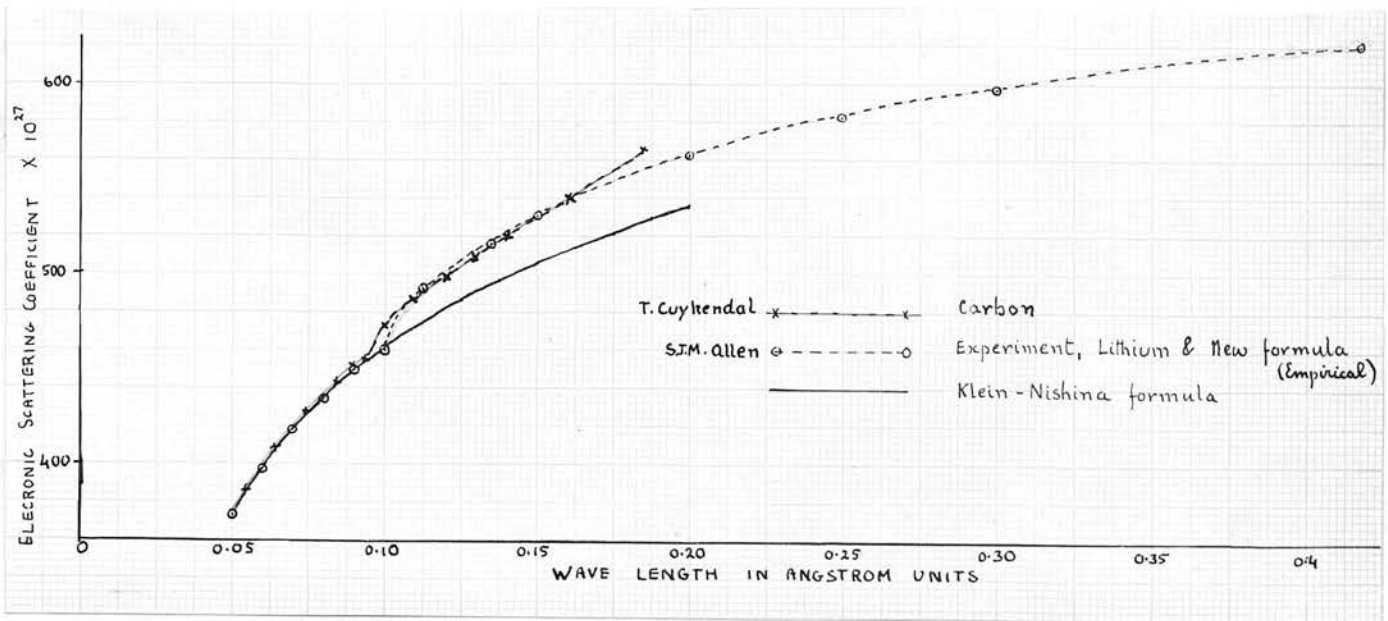


fig 7

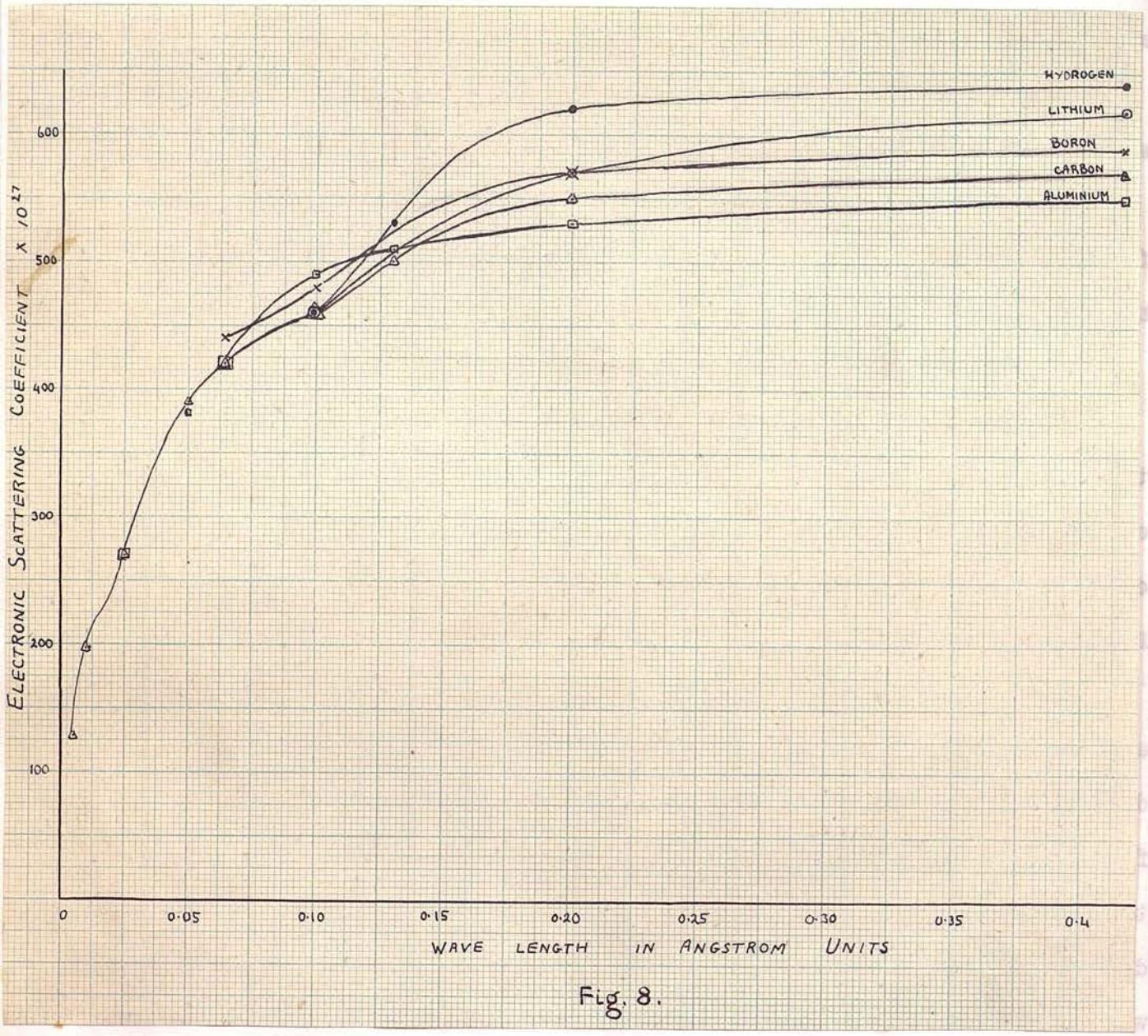

HYDROGEN
LITHIUM
BORON
CARBON
ALUMINIUM
ELECTRONIC SCATTERING COEFFICIENT X 10^{27}
600
500
400
300
200
100
0
0·05
0·10
0·15
0·20
0·25
0·30
0·35
0·4
WAVE LENGTH IN ANGSTROM UNITS

Fig. 8.

Cuykendall, however, did not correct for the absorption associated with the production of characteristic radiation of the scatterer etc.

The corrections have been made by S.J.M. Allen,[15] whose experimental determinations of the electronic scattering coefficients for different wavelengths and different elements are shown in TABLE III, and are plotted for Hydrogen, Lithium, Boron, Carbon and Aluminium in Fig. 8.

TABLE III

ELECTRONIC SCATTERING COEFFICIENT $\times 10^{27}$

ELEMENT	WAVELENGTH IN A.U.								
	0·005	0·010	0·025	0·050	0·064	0·098	0·130	0·200	0·417
H	128	195	270	380	410	460	530	620	640
Li					410	460		570	620
Be								580	600
B					440	480		570	590
C	128	197	270	390	420	460	500	550	570
N								540	
O		195			420	460		520	540
Ne								530	
Na					430	490		540	550
Mg					410	470		540	540
Al	129	197	270	380	420	490	510	530	550

The writer would particularly like to draw attention to the marked point of inflection occurring in both Allen's[15] and Cuykendall's curves at a wavelength of about 0·1 Å.U., and this point of inflexion will be discussed later.

In the mean time it is sufficient to state that the writer finds that an empirical formula of the type

$$\sigma_e = \frac{8\pi}{3}\frac{e^4}{m^2c^4}\left(1 - \frac{4}{\pi}\frac{h}{mc}\frac{1}{\lambda}\right) \qquad (9)$$

agrees with the experimental values of the electronic scattering coefficients for Lithium, for wavelengths between the above mentioned point of inflexion and 0·4 Å.U., and possibly for longer wavelengths as well. This formula will be considered again in 'Discussion of results'.

Compton, Breit, Dirac and Klein and Nishina have attempted to explain the decrease in the electronic scattering coefficient with decrease in wavelength of incident radiation in terms of the photon theory of radiation. Of these formulae, Klein Nishina's[16] formula appears to be the more reliable, and for wavelengths below 0·10 A.U. it seems to be in very good agreement with experiment

$$\sigma_\epsilon = \frac{\pi e^4}{m^2c^4}\,2\left\{\frac{1+a}{a^2}\left[\frac{2(1+a)}{1+2a} - \frac{1}{a}\log(1+2a)\right] + \frac{1}{2a}\log(1+2a) - \frac{1+3a}{(1+2a)^2}\right\} \qquad (10)$$

where $a = \frac{h\nu}{mc^2}$;

The experimental values for the electronic scattering coefficients for wavelengths above about 0·1 A.U. are invariably higher than those predicted by the Klein Nishina formula, and this fact will be considered more fully when we

are discussing the experimental results reported in this work.

It appears that the Klein-Nishina formula predicts the presence of a small amount of unpolarised radiation in the beam scattered at 90° to the incident radiation, the intensity of this unpolarised component is supposed to vary as the square of the frequency, and appears to have been observed experimentally by E. Rodgers,[17] whose technique, however, is not beyond criticism, and so the presence of the unpolarised scattered component cannot be accepted completely.

Compton has shown that the presence of this unpolarised component, if it really exists, can be accounted for in terms of the classical theory, if the spins of the electrons be taken into account.

THE CHARACTERISTIC RADIATION.

The wavelengths of the characteristic radiations emitted by irradiated matter depends on both the atomic number of the irradiated element, and to a certain extent on the wavelength of the incident radiation.

The characteristic radiations from a given element are called the K L M and N----- radiations, and the K radiations represent the highest frequency characteristic radiations which a given element can emit when irradiated by radiation of frequencies higher than the K.

For elements of low atomic number, the characteristic radiations are very absorbable, and are in fact almost completely absorbed in a few centimetres of air around the irradiated elements. In order to investigate the true

scattering of X-rays, it is convenient to use scatterers of low atomic number for this reason.

If this is done, the characteristic rays from the scatterer need not be taken into consideration.

THE PHOTO-ELECTRONS AND RECOIL ELECTRONS.

Both these corpuscular radiations are very absorbable, and, themselves, do not play any important part in our experiments as they never enter into the ionisation chambers. But as these electrons can have very high velocities, and if brought suddenly to rest, produce what are called tertiary X-rays, having wavelengths comparable with those of the incident radiation, these radiations may, to a certain extent, prove troublesome in our work. The intensity, however, of the tertiary radiations arising in this manner is quite negligible compared with the intensity of the incident, transmitted and scattered radiations.

PRINCIPLES OF THE EXPERIMENT.

Filtering Experiment.

Some years ago, experimental investigations by Barkla on the absorbability of heterogeneous scattered radiations seemed to show that the scattered radiations, under certain conditions, appeared to be of precisely the same absorbability as the transmitted radiation - contrary to the expectations from the quantum theory, according to which the scattered radiations were of longer wavelength and, therefore, were more easily absorbed by a given substance than the transmitted radiations.

In earlier work Barkla had shown that the mass absorption coefficient was in reality made up of several separate mass absorption coefficients thus:

$$\frac{\mu}{\rho} = \frac{\sigma}{\rho} + \frac{\tau_K}{\rho} + \frac{\tau_L}{\rho} + \text{-----} \qquad (11)$$

where $\frac{\sigma}{\rho}$ was the mass absorption coefficient due to scattering,

$\frac{\tau_K}{\rho}$ was the mass absorption due to production of the K characteristic radiations of the absorber,

$\frac{\tau_L}{\rho}$ was the mass absorption coefficient due to production of the L characteristic radiations of the absorber

and so on.

Barkla also showed that $\frac{\sigma}{\rho}$ was very small (in particular for Carbon it had a value of 0·2) and in fact, almost negligible in comparison with the mass absorption

coefficient $\frac{\tau}{\rho}$ corresponding to absorption by production of characteristic radiations. He further showed that these $\frac{\tau}{\rho}$ coefficients were proportional to the cube of the wavelength, thus:

$$\frac{\tau}{\rho} = a\lambda^3 \; ; \quad \frac{\tau}{\rho} = \beta\lambda^3 \; ; \quad \frac{\tau}{\rho} = \gamma\lambda^3 \; ;$$

for a given element

where α, β, γ are constants, so that the total mass absorption coefficient $\frac{\mu}{\rho}$ may be written as

$$\frac{\mu}{\rho} = \frac{\sigma}{\rho} + a\lambda^3 + \beta\lambda^3 + \gamma\lambda^3 + \text{- - - - -}$$

$$= \frac{\sigma}{\rho} \pm \left(a + \beta + \gamma + \cdots\right)\lambda^3 \qquad (12)$$

If the mass scattering coefficient is assumed to be independent of the wavelength, (which in point of fact, we have seen on P. 22 not to be the case) and negligibly small, then the mass absorption coefficient of homogeneous radiation of wavelength λ in a given absorber should be proportional to the cube of the wavelength.

If now, by a system of apertures in lead screens, we allow a beam of monochromatic X radiation to fall on a slab of some material used as a scatterer, and select a transmitted beam and a beam scattered at 90° to it and compare the intensities of the two beams by means of suitably designed and placed ionization chambers, using the deflection of the electroscope produced by one of the beams as a standard, we can compare the absorbabilities of the two beams by placing in the path of each of the beams at F_1 and F_2, Fig. 9, equal thicknesses of absorbing filters of, say, aluminium. If the wavelength of the radiation scattered at 90° to the transmitted

radiation undergoes an increase in wavelength in accordance with Compton's theory, we would expect, from equation (12) that the intensity of the radiation reaching the ionisation chamber S to be reduced more than that entering the ionisation chamber P.

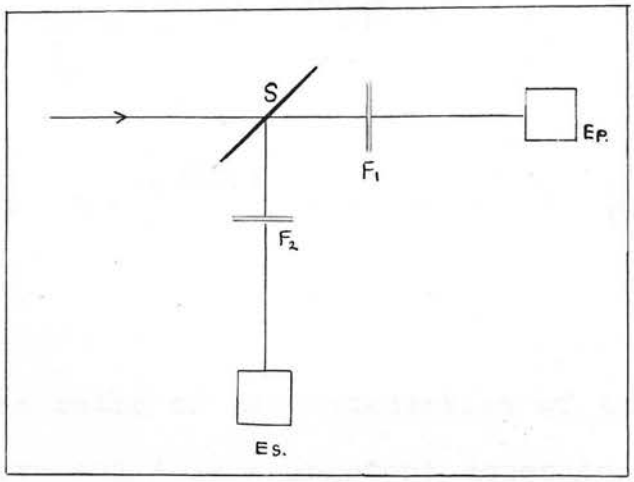


Fig. 9

If we denote the linear absorption coefficient of the transmitted radiation by μ_P and that of the scattered radiation by μ_S we have :

$$\mu_P = \kappa\lambda^3 \quad ; \qquad \text{and} \qquad I_{X_P} = I_P\, e^{-\kappa\lambda^3 x} \quad ;$$

where K is a constant, depending on the absorber, I_X is the intensity of the radiation transmitted through the absorber of thickness x and I_p intensity of the radiation falling on the absorber.

Similarly for the scattered beam we have :

$$\mu_S = \kappa(\lambda + \delta\lambda)^3 \quad ; \quad \text{and} \quad I_{X_S} = I_S\, e^{-\kappa(\lambda+\delta\lambda)^3 x} \quad ;$$

where K is the same constant as above and $d\lambda$ is the increase in wavelength which takes place on scattering according to

Compton's Theory.

The ratio of the intensities of the two beams after passing through the equal thicknesses of filters may then be written as

$$\frac{I_{x_s}}{I_{x_p}} = \frac{I_s}{I_p} e^{\kappa\left[\lambda^3-(\lambda+\delta\lambda)^3\right]x}$$

$$\frac{I_{x_s}}{I_{x_p}} = R e^{-A\lambda^2\delta\lambda x} \quad - - - - - \quad (13)$$

where R is the ratio of the intensities of the two beams without filters and A is a constant depending on the atomic number of the absorber. Terms involving $(\delta\lambda)^2$ and higher powers of $\delta\lambda$ have been neglected.

If we assume that the intensities of the two beams can be compared by the ionisations they produce in a given time, then the curve obtained by plotting $\frac{I_{xs}}{I_{x_p}}$ against the thickness x of the filter should, according to equation (13), be of an exponential form somewhat as shown in Fig. 10.

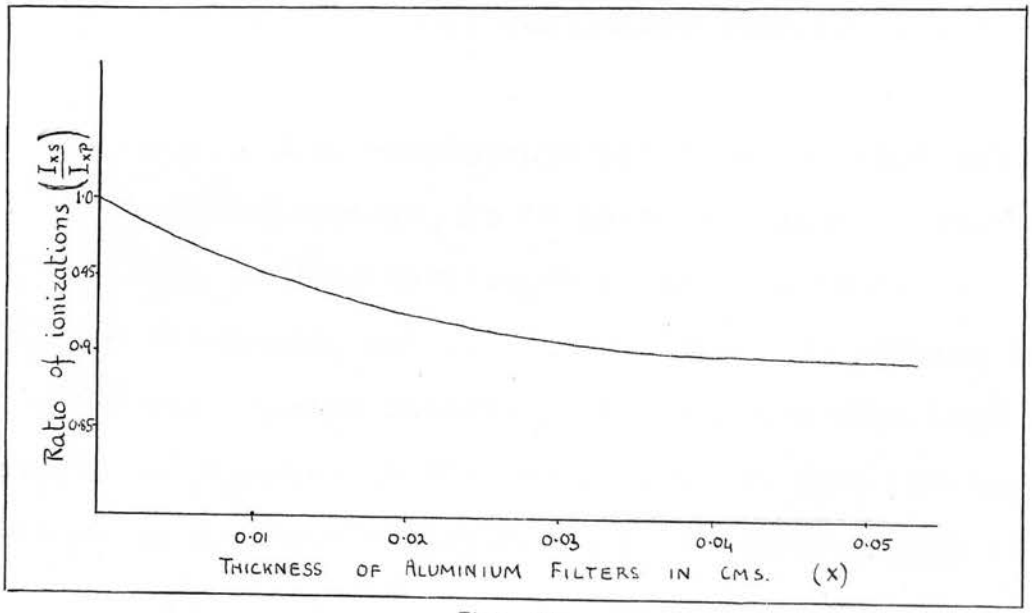


Fig. 10

In practice, however, it is generally rather difficult to carry out an experiment as discussed above, with monochromatic radiation, as this generally involves reflection of radiation from suitably orientated crystals and thus invariably gives monochromatic radiation of very low intensity which can hardly be used for an experiment of the above type.

Another way of obtaining a fairly monochromatic beam of rather higher intensity was devised by P.A. Ross, using the K radiation of the anticathode isolated to within a very narrow wavelength band by the use of balanced filters made of elements whose atomic numbers are on either side of that of the element comprising the target of the X-ray tube. This method, however, also gives intensities too low for the type of experiment considered.

In view of these difficulties, Barkla and his school were obliged to use the general radiation emitted from various tubes and attempted to obtain a certain degree of monochromatisation by passing the radiation through fairly thick filters of low atomic number (so as not to complicate matters with characteristic radiations emitted by the filters).

When performing experiments of the above type with heterogeneous radiations, it is most important to bear in mind that the average wavelength of the two beams is gradually decreased, not at the same rate, on passing through progressively thicker absorbing filters, and also that the ionisations produced in the two ionisation chambers may vary relative to one another depending on the wavelengths of the

components constituting the two beams. These points will be returned to and discussed in full when we discuss the results obtained in this work.

It is sufficient to state for the present, that on performing the above experiments with the general radiations from various tubes excited at various voltages, the result obtained was quite contrary to expectation and was somewhat of the form shown in Fig. 11.

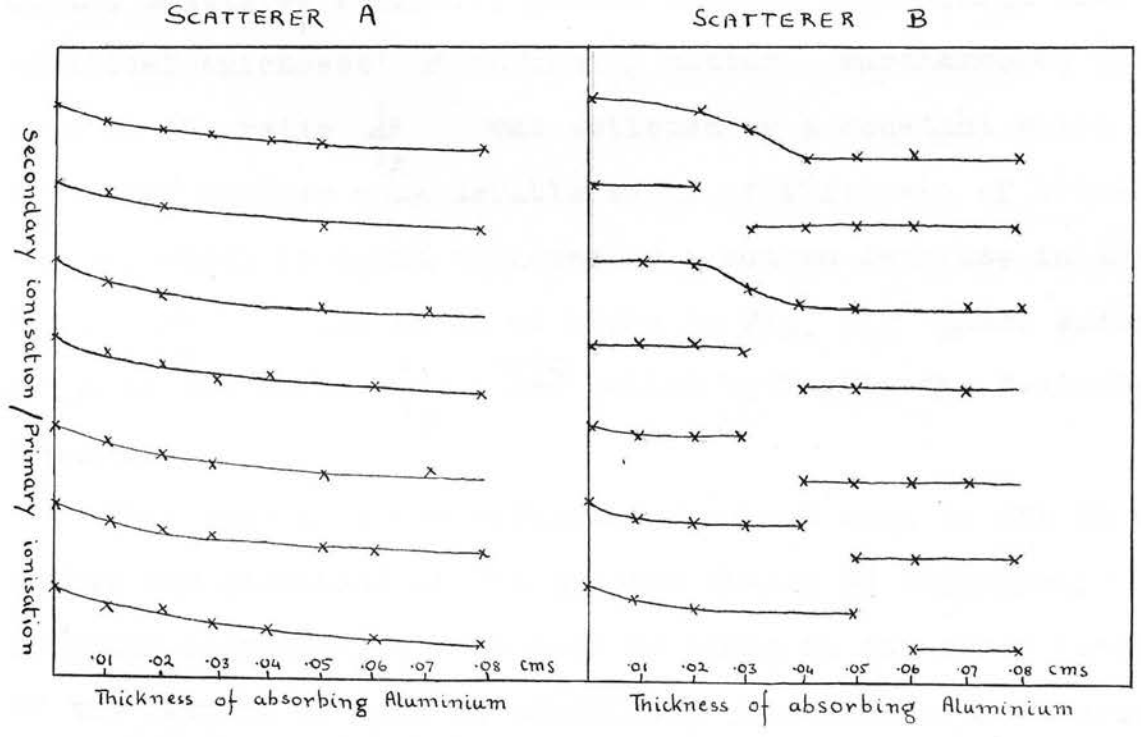


Fig 11.

(From Barkla & Kay. Phil. Mag. Vol xvi, 1933, p 461)

Although sometimes the type of curve predicted by theory based on a change in wavelength of the scattered radiation was

obtained, in fact the conditions governing the type of curve obtained in the experiment does not seem to be known yet.

The most remarkable feature of the experimental curve is that for a considerable thickness of absorbing filter in the transmitted and scattered beams, the ratio of the ionisations (which the beams produce in their respective ionisation chambers, and therefore, presumably also the ratios of their intensities) is constant and the greater absorbability of the scattered radiation appears as a sudden drop in the ionisation ratio, presumably associated with a sudden change in intensity as the scattered radiation passes through what seemed like a 'critical thickness' of absorbing matter. Furthermore, the drop in the ratio $\frac{I_s}{I_p}$ was followed by a constant value of $\frac{I_s}{I_p}$ for another considerable range of thickness of absorbing filter, which is again followed by a sudden decrease in the ratio $\frac{I_s}{I_p}$, and so on as shown in Fig. 11. These sudden drops in the ratio $\frac{I_s}{I_p}$ were called by Barkla the J-discontinuities.

This type of curve obviously does not seem to fit in with either the classical or the quantum theory of radiation, although considerable care must be taken in the interpretation of the results of such an experiment performed with heterogeneous radiation, owing to the difference of ionising powers of radiations of different wavelengths. This point will be discussed again when we discuss the results of the experiments reported in this work.

As already mentioned, the experimental results obtained under what seemed to be identical experimental conditions often gave curves showing the J-discontinuities and sometimes, for no

apparent reason, gave a roughly exponential smooth curve as required by the supposition of a change in wavelength of the scattered radiation.

This fact seems to show that the phenomena of scattering of radiation probably involves some as yet unknown factor or factors, and considerable work was done in this laboratory by Barkla and his school to try and discover the nature of these factors and their bearing on the nature of radiation in general. The results of this research have been published and appear to be most interesting and at the same time somewhat baffling.

Some particularly striking work by Kaye[18] seemed to show that the appearance or non-appearance of the J-discontinuities seemed to depend on the scatterer, in particular one scatterer of paraffin wax gave curves showing marked regions of constant $\frac{I_s}{I_p}$, and another scatterer also of paraffin wax, and of identical dimensions, gave a smooth curve. Unfortunately Kaye's scatterers do not seem to have been preserved. According to his results, it seemed likely that the chemical composition of the scatterer may have some effect in governing the type of curve obtained, but unfortunately the chemical composition of paraffin wax varies considerably from one specimen to another, the wax being really a mixture of a large number of hydrocarbons and not a true compound.

The present writer has attempted to investigate the effect of the chemical composition of the scatterer on the nature of the curve obtained by using scatterers made of Metallic Lithium (98°/o pure), Beryllium Oxide, Boron, Carbon,

Paraffin wax (solid and liquid scatterers), and Aluminium. The results obtained are reported in this paper.

The presence of the horizontal portions of the $\frac{I_s}{I_p} - x$ curve, between the J-discontinuities seem to suggest that between these discontinuities the transmitted and scattered radiations have the same absorbability in the aluminium filters, and consequently, presumably the same wavelengths. We have seen from Woo's spectral analysis of the radiation scattered at 135° by various elements (Page 15) that when the incident radiation was the Ag K_α line, all the radiation scattered by Lithium at that angle was of the modified type, the unmodified scattered radiation being apparently absent. In other words, using a pure Lithium scatterer, according to Woo's results, all the radiation scattered at 135° is of longer wavelength than the transmitted radiation, so that with a Lithium scatterer we would not expect any regions of equal absorbability of the transmitted and scattered radiations at this angle, and it seems reasonable to assume that with wavelengths considerably shorter than the Ag K_α radiation, all the radiation scattered at 90° to the transmitted radiation will also be only of the modified or longer wavelength type, and therefore there should not be any region of equal absorbability of the transmitted radiation and radiation scattered at 90° to it.

The actual results obtained with Lithium scatterers are given further on and it is sufficient to state at present that such horizontal parts of the curve showing equal absorbability of the transmitted and scattered radiations were found to exist under certain conditions with the Lithium, Beryllium

Oxide and Boron scatterers.

One of the well established properties of the J-discontinuities is their dependence on the Potential Difference applied to the X-ray tube generating the incident radiation. Some workers find that as the potential difference across the tube is increased, the positions of all the J-discontinuities are displaced to the left, i.e. occur at smaller 'critical' thicknesses of absorbing filters. Others find the inverse effect. The nature of the J-discontinuity also appears to change from time to time under what seem to be identical conditions of the experimental parameters. Sometimes the discontinuity occurs suddenly at a well defined thickness of absorbing filter. Sometimes it occurs as a 'J-discontinuity region' defined by the fact that for certain thicknesses of Aluminium, the ratio fluctuates at random between two well defined levels, but on either side of this region corresponding to a thickness of about 0·05 to 0·1 mm. of aluminium the ratio $\frac{I_s}{I_p}$ is very steady and constant over considerable ranges of thickness of filtering aluminium and invariably has a higher value on the left side of 'fluctuation region' i.e. for thinner filter thicknesses, than on the right side of the 'fluctuation region', as shown in Fig. 12.

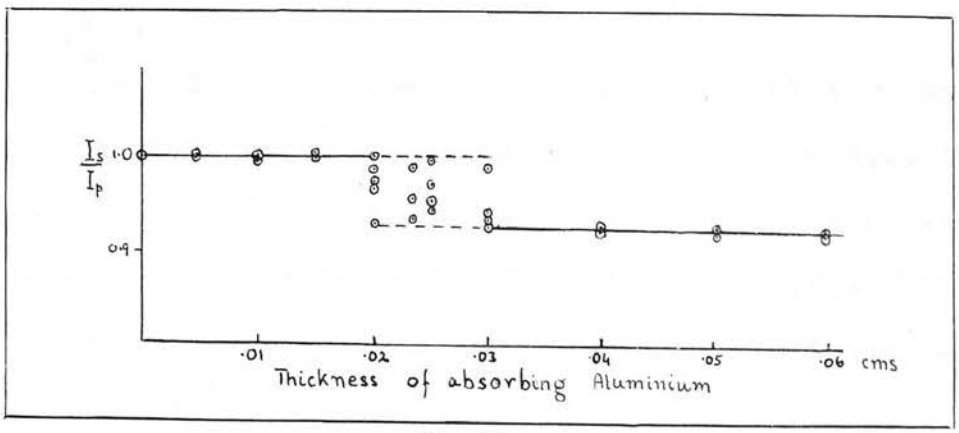


Fig 12.

In recent years, most experimenters working in this laboratory did not seem to find a definite discontinuity in the form of a sudden sharp change in the ratio $\frac{I_s}{I_p}$ from one level to another, but found that the ratio $\frac{I_s}{I_p}$ is the same without any absorbing filters (except for the windows of the ionisation chambers) as it is for thin filters, up to about 0·3 or 0·4 millimeters in thickness, after which an increase in the thickness of the absorbing filters is associated with a gradual decrease in the ratio $\frac{I_s}{I_p}$, more or less exponential in form and as shown in Fig. 13.

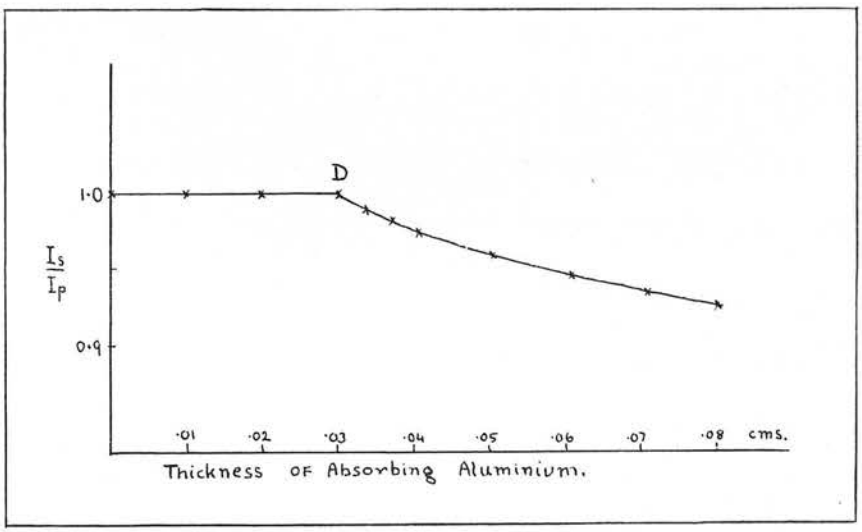


Fig. 13.

In this case we do not get a definite discontinuity in the ratio $\frac{I_s}{I_p}$ but a marked and well defined point of inflection, D which appears instead of the discontinuity in the levels of $\frac{I_s}{I_p}$.

The point of inflection, D, does not always occur, but when it does, again suggests that for thin absorbers the absorbabilities of the transmitted and scattered radiations are the same, but after passing through a critical thickness of matter, the scattered radiation appears to be markedly

more absorbable than the transmitted radiation. This result again seems to be in contradiction to classical and quantum theories, and will be discussed more fully later.

EXPERIMENTS ON FILTERING HETEROGENEOUS RADIATION BEFORE SCATTERING.

As already mentioned, when heterogeneous radiation such as the general radiation from an X-ray tube is filtered through some element of low atomic number, the intensities of the various components of the heterogeneous radiation are decreased by varying amounts in accordance with the absorption law, so that the transmitted radiation will contain a relatively greater intensity of shorter wavelength components than of the longer wavelength components, and will thus have a shorter 'average' wavelength.

Now, according to Compton's theory of scattering, the change in wavelength of the scattered radiation is a function of the angle of scattering only, and is independent of the wavelength of the incident radiation, and consequently the shorter the wavelength of the incident radiation, the greater will the relative, or percentage change in wavelength be, and therefore the greater the difference in the absorbabilities of the transmitted and scattered radiations.

The ionisations produced by the scattered and transmitted beams in two similar ionisation chambers, is principally due to the ejection of photo electrons by the absorption of the radiations in the gas in the ionisation chambers, and as such, the ionisations produced should be an exponential function of the wavelength cubed, (the λ^3 absorption law has been shown to be applicable to absorption by gases).

Thus, if we progressively harden the radiation falling

on a scatterer and compare the ionisations produced by them, we should expect the ratios of the ionisations $\frac{i_s}{i_p}$ to increase as the average wavelength of the incident radiation is decreased, owing to the relatively greater difference in the absorbabilities of two beams arising as already described.

There are two ways in which the general radiation from an X-ray tube can be hardened, one being by increasing the potential difference across the tube, and the other by a process of filtering through some suitable absorber which removes the energy in the longer wavelengths more strongly than the energy in the shorter wavelength components.

In the first case the variation of the intensity distribution of the components of the general radiation with the potential difference across the tube is as shown in Fig. 65′ , p 136 , and we may represent the results of such an experiment by plotting the ratio of the ionisations $\frac{i_s}{i_p}$ against the Kilo voltage across the tube on the assumption that the average wavelength of the radiation is some function of the potential difference. This function is, however, not known to any degree of certainty, and this method of presenting the results of such an experiment is therefore rather limited in value.

Similarly when hardening the incident radiation by filtering through suitable absorbers, we can plot the ratio of the ionisations $\frac{i_s}{i_p}$ against the thickness of the filter, and attempt to interpret the result on the assumption that the average wavelength of the transmitted radiation is some function of the thickness of the filter,

but here again the procedure is not of very great practical use.

Generally, when an experiment of this type is carried out, it is most convenient to use both methods of hardening the radiation.

For example, starting with fairly soft general radiation with the tube excited at about 30,000 volts, the ionisation ratio $\frac{i_s}{i_p}$ is observed as the voltage is raised to 40,000, 50,000 etc. consecutively; the limit of the voltage that can be used is set by the source of the potential, (an induction coil, transformer or constant high tension generator) or by the rating of the X-ray tube used. When this upper limit to the hardness of the general radiation has been reached, we can maintain the maximum potential difference across the tube and further harden the radiation by filtering out the softer components by passing the radiation through a suitable absorber of low atomic number, in this case aluminium is commonly used.

If, however, the above methods of presenting the results are used, it is very difficult, if not impossible, to compare the variation of the ionisation ratios $\frac{i_s}{i_p}$ with the hardness of the radiation produced by the two methods. This difficulty can be removed by plotting the ionisation ratios against the mass absorption coefficients of the transmitted radiation measured conventionally by a 50% reduction in intensity by the interposition of a suitable thickness of aluminium as already described on page 7 . The resulting curves obtained by some workers in this laboratory are somewhat as shown in Fig. 14.

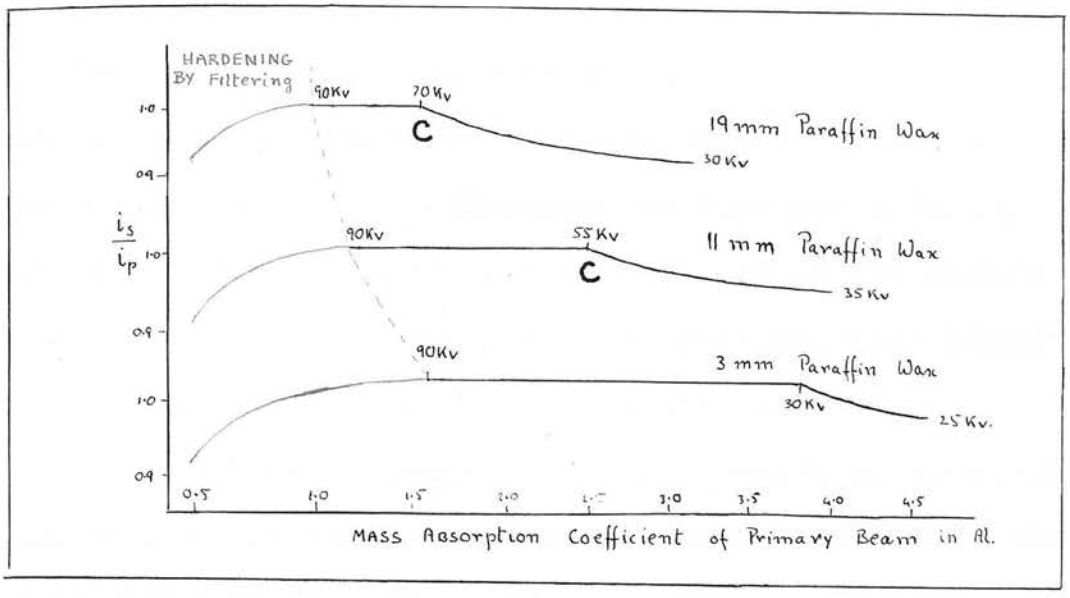


Fig 14

Other workers in this department - but in another laboratory - seem to obtain results as shown in Fig. 15.

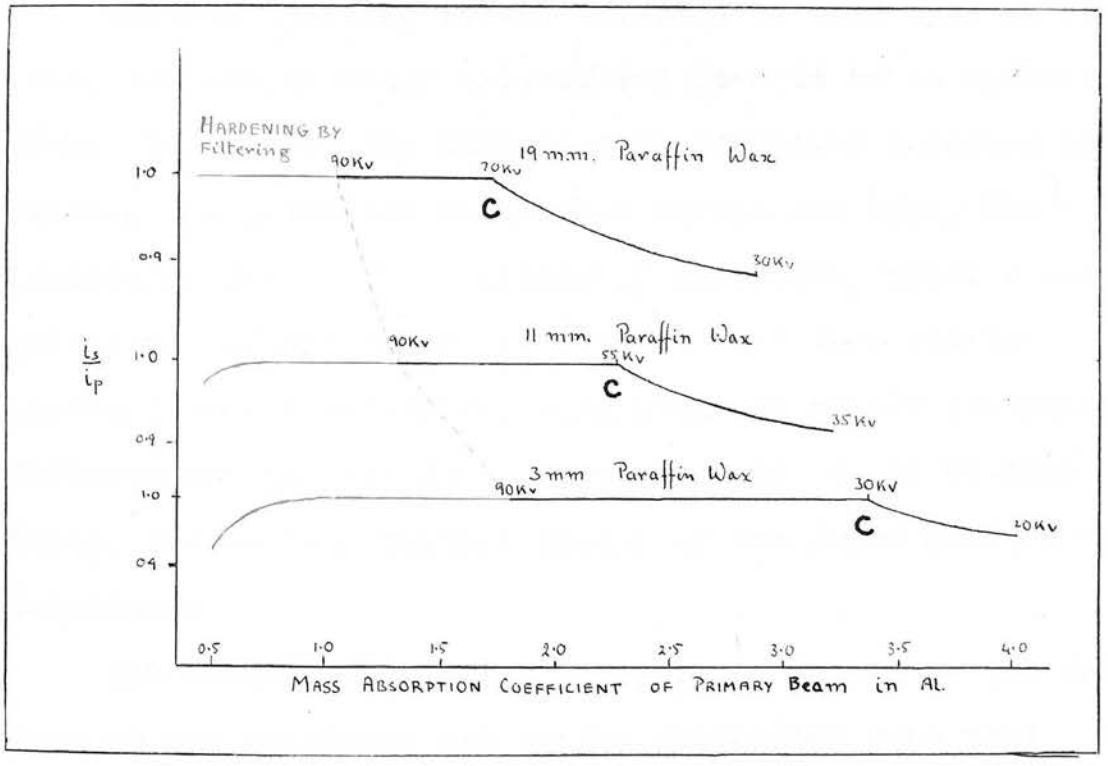


Fig 15.

The main difference in the two sets of results lies in the fact that the latter results, obtained with the thicker Paraffin Wax Scatterers, seem to show a remarkable constancy

of the ionisation ratio $\frac{i_s}{i_p}$ when the radiation is hardened by passing through considerable thicknesses of Aluminium filter, whereas the former results seem to show that the ionisation ratio $\frac{i_s}{i_p}$ decreases as soon as filtering is commenced, irrespective of the thickness of the Paraffin Wax scatterer, although the effect is sometimes more marked with thinner scatterers than with thicker ones.

The problem of determining the conditions governing the constancy or otherwise of the ionisation ratio when the beam is hardened by filtering through Aluminium has been carefully investigated in this work and the results and conclusions reached are reported below.

Another striking effect revealed by this type of experiment, and one in which all workers seem to be in agreement about, is that as the radiation is gradually hardened by raising the potential difference across the tube, the ionisation ratio $\frac{i_s}{i_p}$ gradually increases, until a certain potential difference C is reached, and then remains constant over a relatively wide range of higher potential differences, in fact for potentials from C to 90-Kilo Volts, the maximum voltage rating of the tubes used in this laboratory.

The actual value of C appears to depend on the thickness of the scatterer and on the particular tube used. Thin scatterers give values of C which are lower than those obtained when thick scatterers are used.

The experimental results obtained by using various tubes and scatterers of Li, BeO, B,C, Paraffin Wax and Al by the writer will be described below.

APPARATUS.

APPARATUS I

SCALE: $\frac{1}{5}$ ACTUAL SIZE

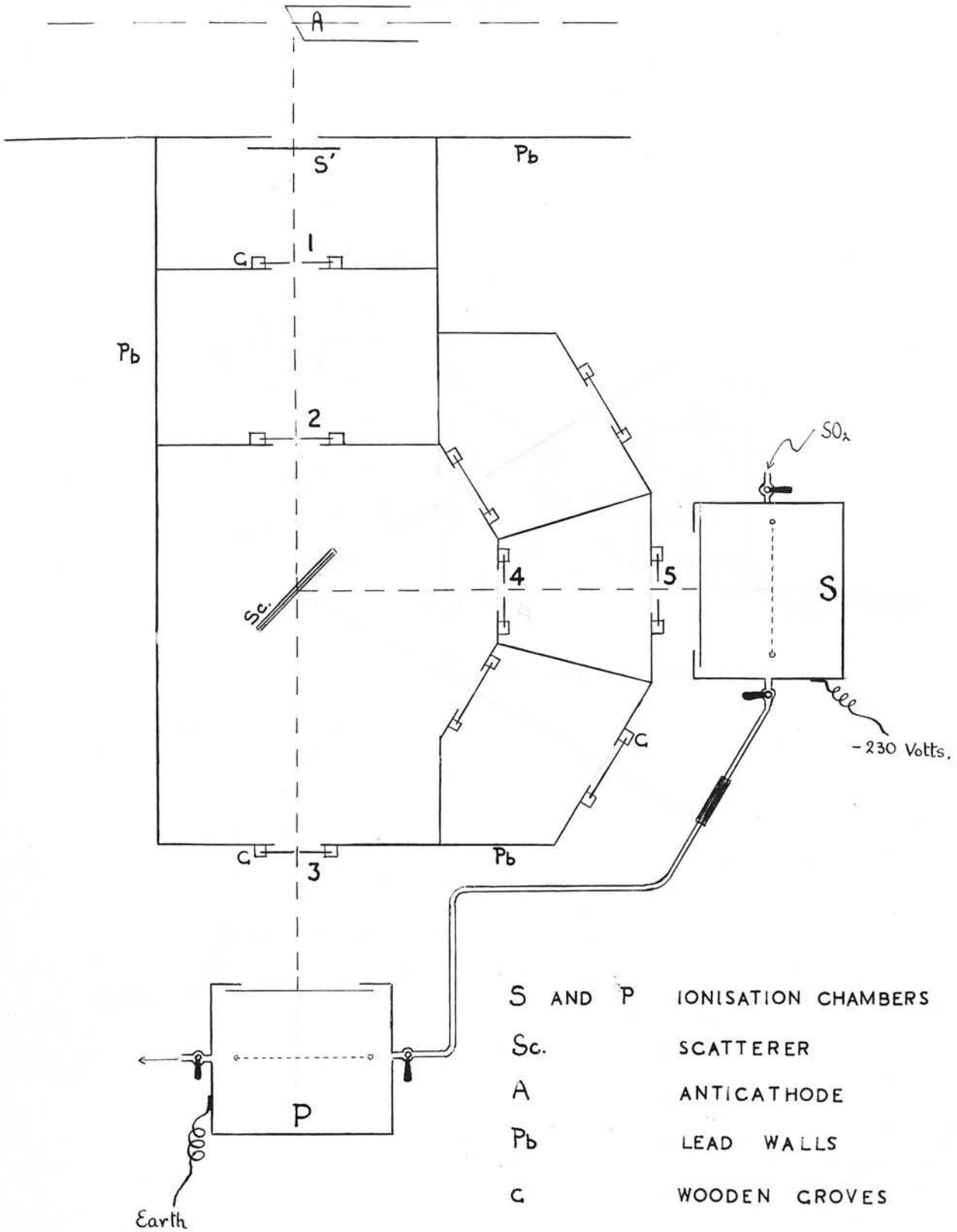
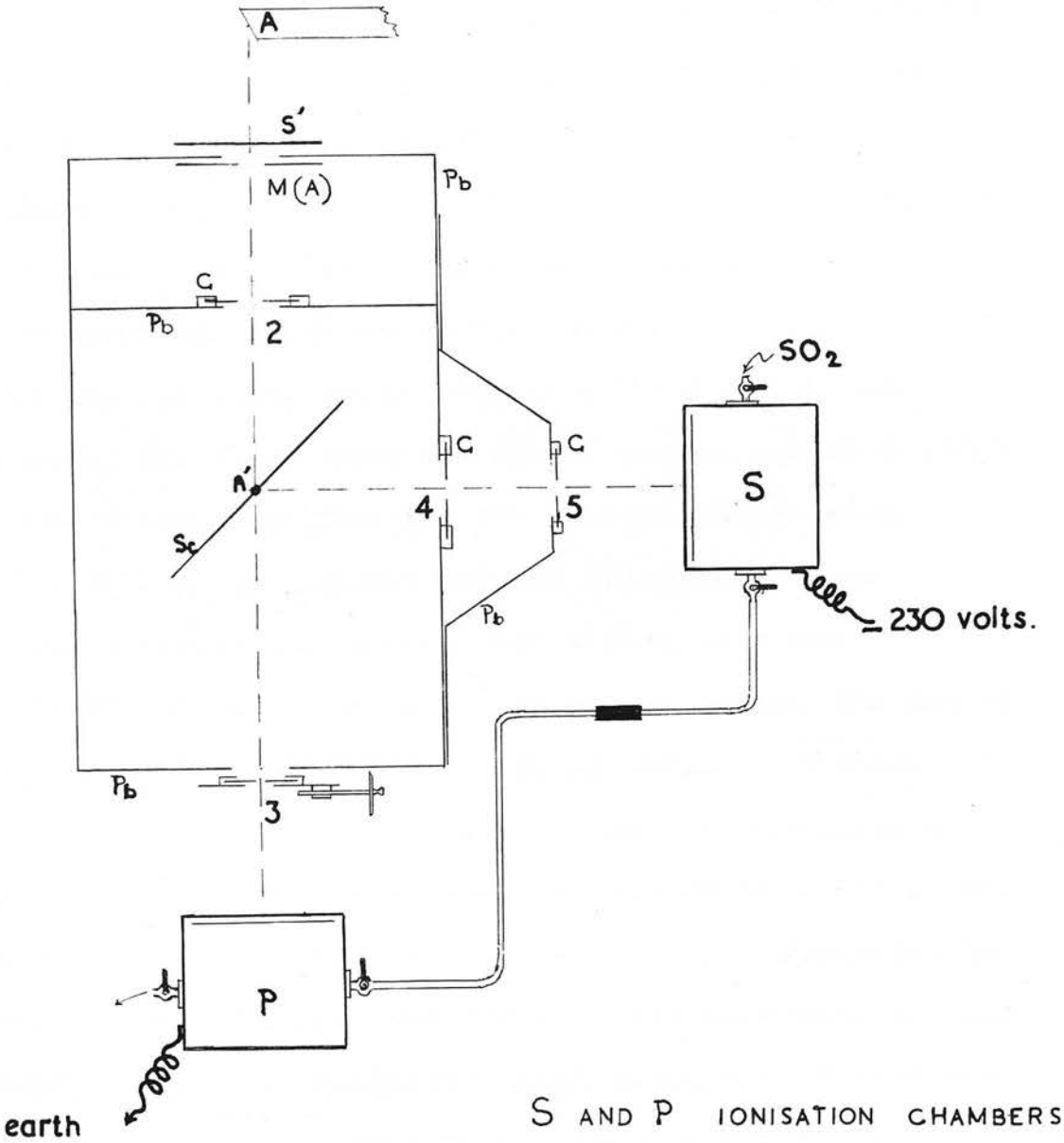


Fig 16

APPARATUS II

scale : $\frac{1}{5}$ actual size



S AND P	IONISATION CHAMBERS
Sc.	SCATTERER
A	ANTICATHODE
Pb	LEAD WALLS
C	WOODEN GROOVES

Fig 17

THE APPARATUS.

(1) Apertures and Screens.

In all the experiments to be described below the properties of a beam of radiation scattered at 90° to the incident radiation (hereafter called the secondary beam) are compared with the properties of the beam transmitted through the scatterer (hereafter called the primary beam).

These beams are obtained by using a suitable arrangement of lead screens having apertures, and the lay out of these screens are as shown in Fig. 16 and Fig. 17.

To prevent stray radiations interfering with the experiment, the X-ray tube was itself placed inside a large lead walled box, the high and low tension leads being inserted through insulators made of 'Micanite' tubes measuring 4 inches in diameter and filled with wax.

The writer has been fortunate enough to get the use of the actual apparatus used by previous workers, Reekie ~~Ritchie~~ and Miss Wilson, and was thus able to carry out experiments under what seemed like identical conditions to those of the above workers. The actual arrangement of this apparatus is as shown in Fig. 16, and the screens used were made of lead measuring 3 m.m. in thickness; this thickness of lead was stated by the above workers to be adequate for the voltages used, up to 105 KV. After obtaining numerous results with this apparatus, the writer was led to the conclusion that the thickness of lead used was insufficient and determined the penetration of the radiation for different thicknesses

of lead by means of a photographic exposure using Ilford Double Coated X-ray film backed by a Calcium Tungstate Screen. The resulting radiograph is shown in Fig. 18 and shows that even for 90 Kilovolt radiation 3 m.m. thickness of lead was insufficient, but 4 m.m. lead was almost opaque to the radiation.

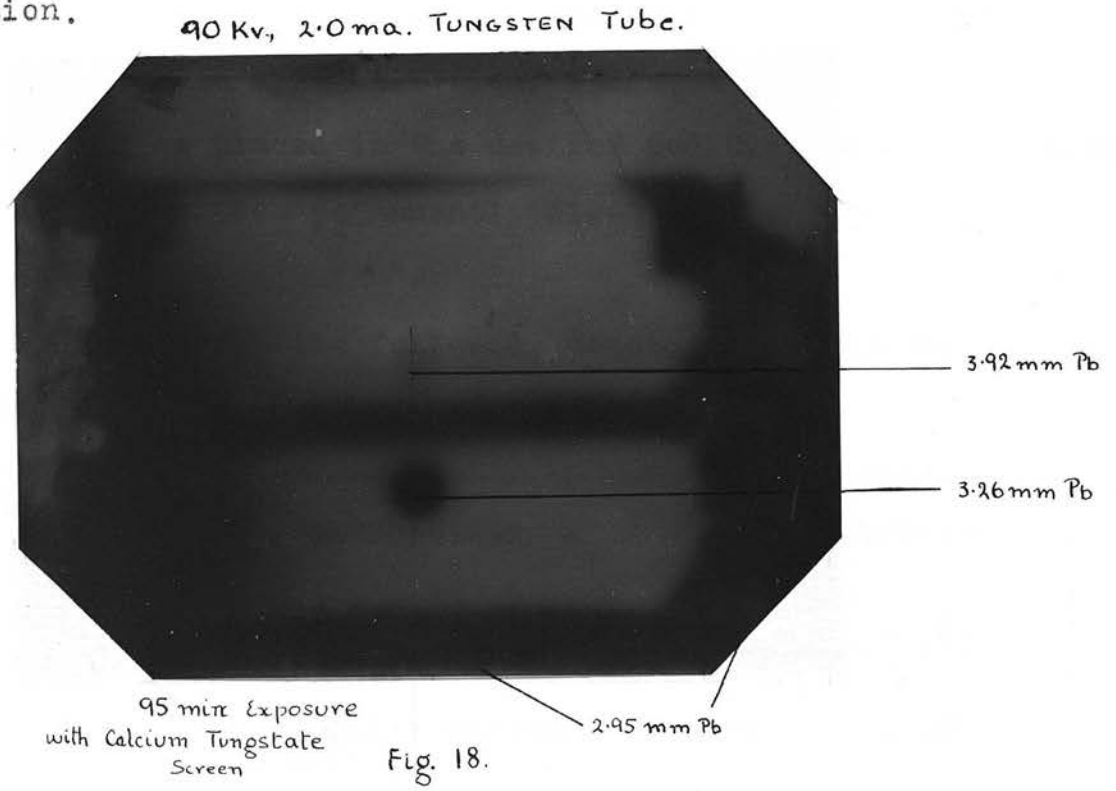


Fig. 18.

It must, however, be emphasised that the photographic method of detecting radiation is generally far less sensitive than the ionisation method, and hence the penetration of the radiation through various parts of the screens may seriously effect the experimental results, particularly when high potentials and long ionisation readings are involved.

To overcome this difficulty, the apparatus was rebuilt with lead screens having 4 m.m. thickness, and in the light of experience gained in the preliminary work with apparatus I the writer has redesigned the lay out of the screens and apertures in an attempt to provide better experimental

conditions, in particular the size of the apparatus was considerably reduced, thereby giving bigger intensities in the beams enabling smaller apertures to be used, and reducing the times of the various readings.

The new, 4 m.m. walled apparatus is shown in Fig. 17.

The apertures were made in separate sheets of lead (3 m.m. thick in apparatus I and 4 m.m. thick in apparatus II) which could be placed in the desired position by sliding them into wooden grooves permanently fixed to the lead walls or screens.

In this work, the following nomenclature for the various apertures has been used:-

Aperture No. (in diagram)	Nomenclature	Notation
No. 1	Main Primary Aperture nearest to tube.	M (A)
No. 2	Main Primary Aperture nearest to Scatterer.	M (B)
No. 3	Primary Aperture.	P
No. 4	Secondary Aperture nearest to Scatterer.	S (A)
No. 5	Secondary Aperture nearest to chamber.	S (B)

The transmitted beam was invariably found to be much more intense than the scattered beam and consequently, the primary aperture No. 3 was usually a very small one, of the order of about 1 m.m. in diameter, whereas the secondary apertures (Nos. 4 and 5) were comparatively large, ranging from about 0·8 cms. to 2·5 cms. in diameter.

In apparatus No. II, the primary aperture No. 3 was mounted on a horizontal micrometer screw, so that it could be given horizontal displacements, and so served to select transmitted beams over a small range of angles; in most of the work, however, this aperture was kept at the central or zero position.

(2) The Scatterers.

In order to eliminate as far as possible any complications brought about by different thicknesses of the scatterer being traversed by the primary and secondary beams, the scatterers used were in the form of vertical slabs, and were inclined at an angle of 45° to the incident radiation. In this way, both beams traversed equal thicknesses of the scatterer, apart from possible multiple scattering, which would in any case, give rise to relatively low intensity scattered radiation, (since the process of multiple scattering is really the rescattering of scattered radiation). The presence of multiple scattering should, however, be borne in mind when interpreting the results obtained, particularly when using thick scatterers.

The thicknesses of the scatterers used ranged from 19 m.m. to 1 m.m. for Paraffin Wax, and were all 10 m.m. thick for scatterers of Metallic Lithium, Beryllium Oxide, Boron, and Liquid Paraffin Wax. For Aluminium scatterers the thickness ranged from 1·28 to 2·06 m.m. and for carbon from 6 m.m. to 9·3 m.m.

The solid Paraffin Wax scatterers were cast by pouring the molten wax into wooden moulds and then planing the cast

slabs to the desired thickness.

The liquid Paraffin Wax scatterer was made by cutting out an oval shaped aperture in a piece of 3-ply wood, 10 m.m. thick, measuring 17 × 14 cms^2; this aperture measured 10 cms. along its major axes and 7 cms. along its minor axes, and the vertical edges were levelled in such a way as to ensure that the incident and secondary radiations never touched the wood when the latter was placed at 45^0 to the incident radiation.

The oval aperture was then covered by a piece of wet cellophane which was then glued to the wooden sides with 'secotine'. While the glue was still pliable, the cellophane was evened out and tightly stretched, and when dry was found to give a remarkably well stretched smooth 'window' over the aperture; the other face of the wooden slab was similarly covered with cellophane, and an opening was made at the top whereby molten wax could be poured into the cellophane cell thus formed.

The thickness of the cellophane used was 0·0 1 cms. and as such produced quite negligible absorption and scattering and the radiation was mainly scattered by the wax between the cellophane faces.
The two heating filament terminals at the top of the were connected
scatterer, to a source of potential difference of 20 volts. The whole of the paraffin wax in the cell was found to melt in half an hour, and so the scatterer could be used in liquid or solid form without the necessity of touching any part of the scatterer or system of apertures. The completed scatterer is shown in Fig. 19.

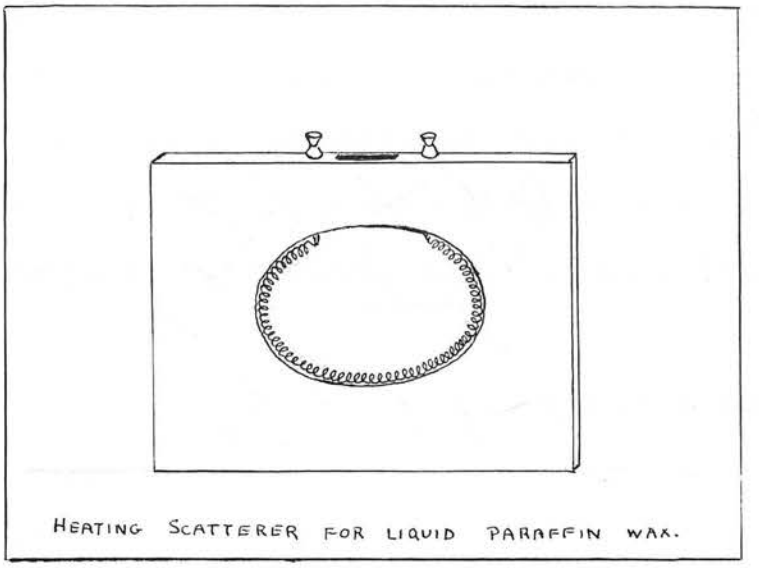


Fig. 19.

The Boron and Beryllium Oxide was only available in very pure powder form, and because of their very high melting points could not be cast into a solid slab. For this reason, several more cellophane wood cells, as described above, were made (without the heating spiral and terminals), and were filled with the pure powdered Boron or Beryllium Oxide. A fairly even density of the powder packing was achieved by gentle but firm tapping of the wooden former during the pouring in of the powders.

With cellophane windows made as described above, no bulge near the centres of the windows was observed. In fact, the windows behaved as well as any plane mirror when tested for reflection; no distortion of an image reflected by either window could be detected.

The metallic Lithium was available in the form of irregular rectangular pieces kept under naphtha oil. Fortunately the metal has a low melting point so that it could be cast into a suitable shape.

Molten Lithium is, however, one of the most reactive substances known and although some attempts were made to cast it in moulds made of graphite or fireclay, these were quite unsuccessful, until, thanks to the kind advice of Dr. Bolam of the Chemistry Department, the following technique was evolved.

The blocks of Lithium were melted in a covered iron crucible, then removed from the Bunsen Burner and the burnt remains of the naphtha oil and oxide film scraped off the molten Lithium as quickly as possible by means of a stainless steel spatula to prevent free access to the atmosphere, and then recovered and allowed to cool. The resulting circular block of Lithium was found to be rigidly stuck to the iron crucible, but as the metal is very soft, it could be levered off the sides of the crucible and the bottom of the crucible sawn off, leaving a thick disc of metallic Lithium which was then beaten out into a roughly circular disc having a thickness of about 1·3 cms. This disc was then placed loosely into an oval shaped aperture in a block of wood 10 m.m. thick, covered on both sides with thick sheets of aluminium and squeezed between these sheets in a vice until the aluminium sheets were everywhere in contact with the wooden block.

In this way, the lithium practically filled the oval aperture and, on removal from the vice, was found to have very smooth metallic faces, which were then polished with a mixture of Amyl Alcohol and Petrol and given a very thin protective film of Vaseline.

When not actually in use, the two faces were further protected from oxidation by sheets of cellophane placed over

the faces and stuck down by a fairly thick layer of vaseline at their edges; these sheets were peeled off when the scatterer was in use.

The Carbon was available in the form of regular rectangular blocks of graphite and were mounted on top of a piece of wood to give the desired height, and held in a vertical plane by aluminium clips at either end, attached to the piece of wood underneath, as shown in Fig. 20.

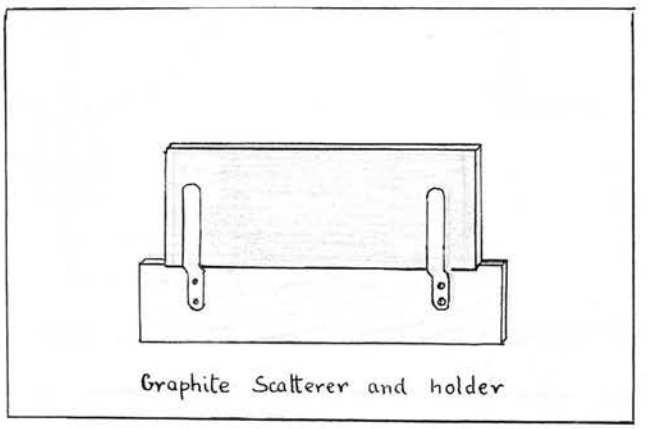
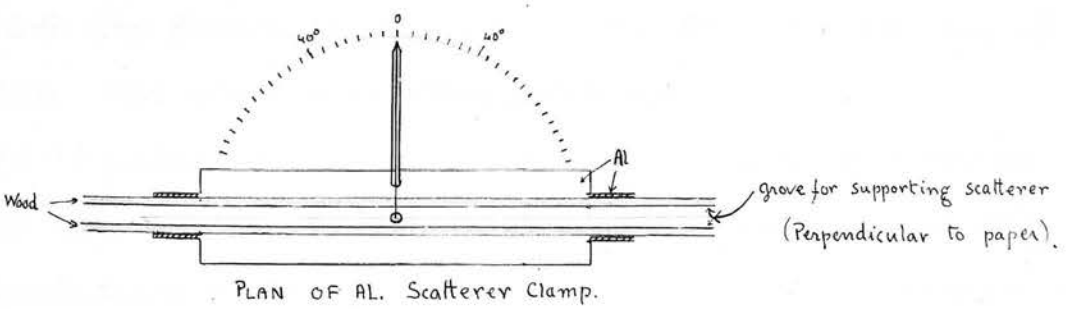


Fig 20

The bases of all these scatterers were clamped between thin wooden strips of suitable thickness which served as packings between the scatterers and the jaws of the aluminium clamp which can be rotated about a vertical axis by means of a short brass axle fitting into a hole A in the base of the lead scattering box, (Fig. 16 and 17), and also carries a pointer moving over a scale graduated in degrees.

The clamp is shown in Fig. 21.



PLAN OF AL. Scatterer Clamp.

Fig 21

(3) The Ionisation Chambers.

The two ionisation chambers were identical with one another in every respect and details of their design are shown in Fig. 22.

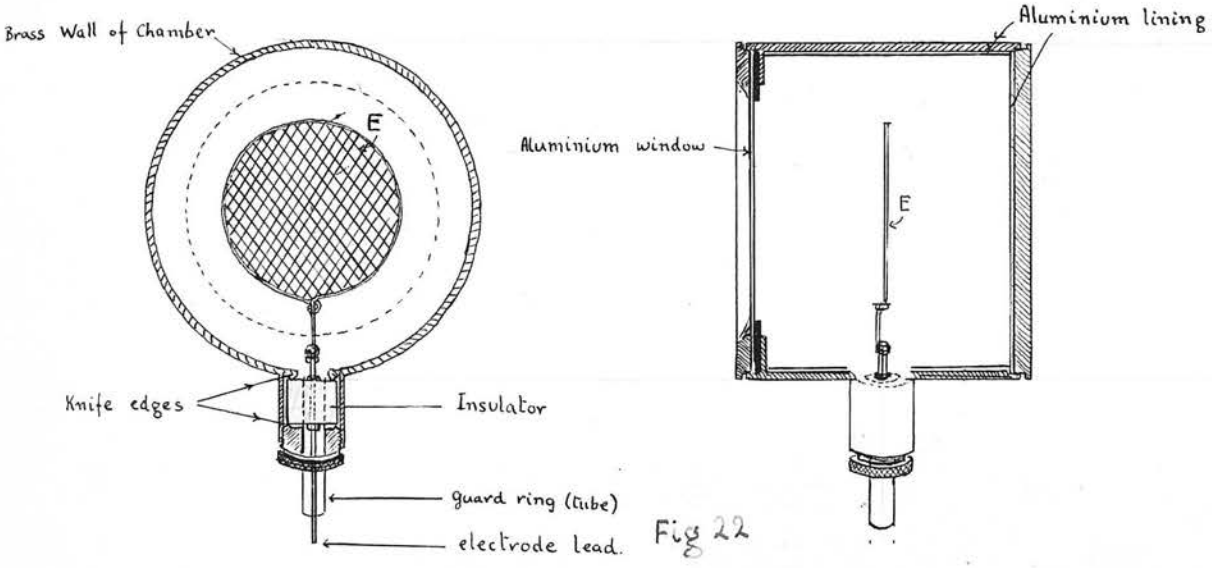


Fig 22

Apparatus I was fitted with rather large ionisation chambers measuring 12·5 × 15·0 cms diam. and the resulting natural leak of the instrument was consequently somewhat on the large side. Smaller ionisation chambers were then substituted, the dimensions were: 9·0 × 11·0 cms diametre, and this greatly reduced the natural rate of leak.

Apparatus II was used with the smaller ionisation chambers throughout. Both sets of ionisation chambers were covered on the outside with 3 m.m. lead.

The electrode E (Fig. 22) was made of an aluminium wire frame, over which was stretched and sewn a piece of fine silk gauze which was generally rendered conducting by a coating of indian ink. But after some experience the writer found Acheson's 'Aquadaq' Colloidal Graphite considerably superior to indian ink, as the graphite gave a much more coherent and better conducting surface, and being pure carbon was chemi-

cally inactive with the gases used in the ionisation chambers, and a poor emitter of photo electrons, this last property being particularly desirable.

During the coating process the colloidal graphite was also used for smoothing down any of the small irregular hairs from the silk gauze, this being important for good performance of the ionisation chamber, as any sharp edges or points are apt to produce brush discharges in the potential gradient existing inside the ionisation chamber.

The electrode was kept in position and supported by the free end of the aluminium wire making up the electrode frame, this end being bent into an eye and rigidly secured to the electrode lead, E.L. passing through the insulating plug, by means of a rounded nut N shown in Fig. 23. The intensities, or strictly speaking, the ionisations produced by the primary (transmitted) and secondary (scattered) beams were compared by observing the number of microscope eyepiece divisions through which the image of the primary gold leaf moves while the image of the secondary gold leaf moves over a standard number of divisions. Corrections for the natural leaks occurring during the time taken by the secondary gold leaf to move through the standard number of divisions are then applied to the observed deflections and the ionisation ratios determined from the resulting values of the corrected deflections.

In actual practice, however, it was found very difficult to apply natural leak corrections because the rates of leak were different at the two positions of the gold leaves corresponding to the zero and the deflected positions. In other words, the rates of leak seemed to depend on the actual

instantaneous potentials of the electrodes.

Careful observation soon showed that this difference in the rates of leak for the various positions of the gold leaves was due to the 'soaking in' of the charge on the electrode into the insulating plug. In particular, the rate of leak at or near the zero position of the gold leaf was invariably higher than that at the end of its deflected range, but as the gold leaf was maintained in the latter position for a time interval of about half an hour, the natural rate of leak gradually rose to the same value it had when the leaf was in its zero position, thereby obviously showing a 'soaking in' effect of the charge acquired by the electrode into the insulator, which initially masks the normal rate of leak.

The writer then undertook a series of experiments to try and determine the cause of the 'soaking in' of the charge and to attempt to reduce them to a minimum or to remove them completely.

These experiments showed the following:-

(1) The 'soaking in' of charge depended on the material of the insulator. Some speciments of ebonite were better than others but generally showed marked 'soaking in' effects, although sulphur seemed to have only a very slight, if any, 'soaking in' property.

(2) The 'soaking in' of charge depended on the potential gradient across the insulator.

(3) The 'soaking in' of charge seemed to be proportional to the area of contact between the metal electrode lead-in and the insulator itself, being markedly less when small insulating plugs were substituted for the larger 3 to 4 cms. ones.

Most previous workers used ebonite insulators with guard rings as shown in Fig. 23.

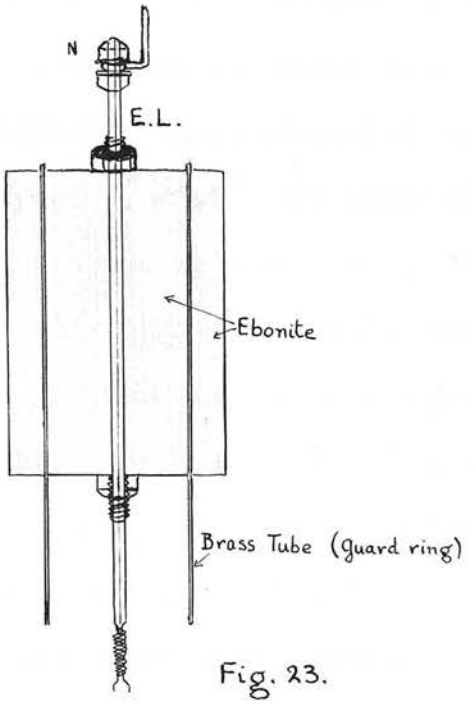


Fig. 23.

But as the writer attempted to use smaller apertures and higher electroscope sensitivities, the soaking in effect was found to be very troublesome and consequently attempts were made to develop a sulphur insulator, but this was not very successful owing to lack of mechanical strength and the difficulty in making a gas tight seal between the sulphur and the metal electrode lead-in, although after some experimentation a combined sulphur-ebonite plug was made which had a very small 'soaking in' effect but these plugs only had very short lives as they rapidly developed gas leaks.

Quartz was then tried but could not be made to give a gas tight seal in any simple way, although the British Thermal Syndicate Co. Ltd. suggested a design for a quartz insulator involving gas tight lead seals; but it seemed that the design would considerably increase the capacity of the electrode systems and would thereby reduce the sensitivities of the electroscopes to ionic charges.

At about this time the writer obtained some very valuable information regarding a new plastic insulation material having the trade name of 'Distrene'. This material has an amazingly high surface resistivity of 3×10^6 megohms after an immersion of 24 hours in water; it is also chemically inert and stable, of very high mechanical strength and easily worked in a lathe. The 'soaking in' effect is practically negligible in Distrene. Accordingly, new insulators were made of this substance, and designed in such a way as to have a very minimum area of contact between the insulator and the metal electrode lead in. This was achieved by having the electrode passing through a wide hole in a cylinder of Distrene so that there is no contact between the metal and the insulator and gripping the insulator between two hollow ground brass nuts having knife edges biting into the distrene; the metal-insulator contact area is thus completely confined to the area of contact between the sharp knife edges and the insulator, thus being of the order of 0·05 sq. cms., compared to the contact area of 4·6 sq. cms. in the usual design.

This design for the electrode-insulator system was originated by the writer and has given remarkably good performance. It combines negligible 'soaking in' of charge with good mechanical strength and is practically gas tight. The electrical capacity of the system is also very low owing to the major part of the dielectric being air.

In recent years, many workers including the writer, have experienced trouble with the insulation due to some as yet unexplained chemical reaction occurring between the Sulphur Dioxide Gas used in the ionisation chambers and the ebonite

insulating plugs, giving rise to a thick white residue which completely destroyed the insulation properties. No such effect was ever observed with Distrene insulators.

The complete Distrene insulating system is as shown in Fig. 24.

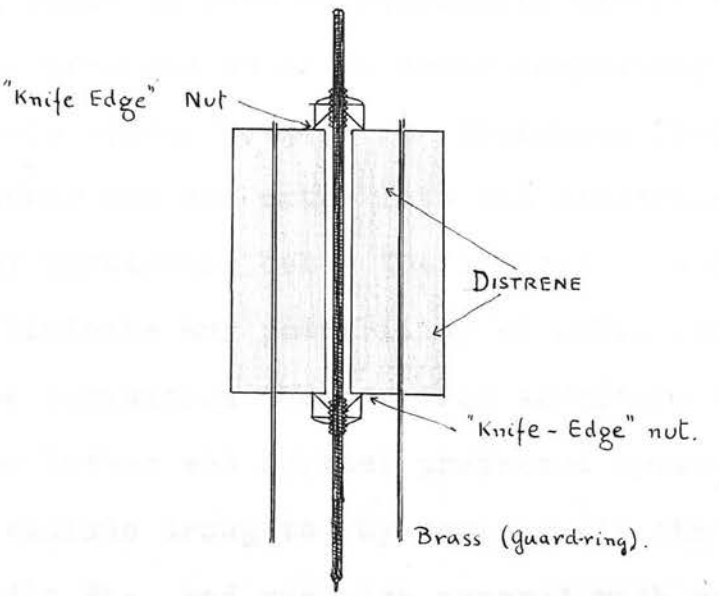


Fig. 24.

(4) The Electroscopes.

Owing to the great difference in intensity of the transmitted and scattered beams, it was convenient to use electroscopes of different sensitivities for the two beams. The intensity of the transmitted beam was about 1000 times that of the scattered beam, and the ionisation produced in the primary ionisation chamber was cut down by using a sufficiently fine aperture, usually of the order of about one or two m.m. in diameter while the ionisation produced by the scattered beam in the secondary ionisation chamber was made comparable with that produced in the primary ionisation chamber by using relatively large secondary apertures generally of the order of one to three cms. in diameter.

The primary electroscope was of the ordinary cubical box type, where the gold leaf was suspended from a central metal electrode, the top of which was connected to the ionisation chamber electrode by means of a thin coiled brass spring, care being taken to have an adjustable sleeve working on the guard ring, arranged so as to cover completely all parts of the electrode system between its emergence from the ionisation chamber and its entry into the electroscope. This was mounted vertically below the ionisation chamber, in order to eliminate any possibility of radiation transmitted through the ionisation chamber from affecting the electroscope. The latter was further protected by making it gas tight (to exclude draughts) by sealing all the openings with Edward's Wax, and was also covered with sheet lead 3 m.m. in thickness. The inside of the brass box was lined with sheet aluminium and several layers of filter paper.

An eccentric ebonite knob, bearing on a brass spring served to charge the gold leaf to the desired potential by connecting the electrode system to the positive terminal of a 240 volt battery, the negative terminal of which, together with the outer casings of the electroscope and ionisation chamber was earthed, thereby producing a potential gradient of 240 volts between the electrode and case of the ionisation chamber, which drove negative ions towards the electrode.

The above potential also produced a deflection of the gold leaf of about 25°.

The gold leaf and electrode system could then be isolated by means of the eccentric knob, and the rate of

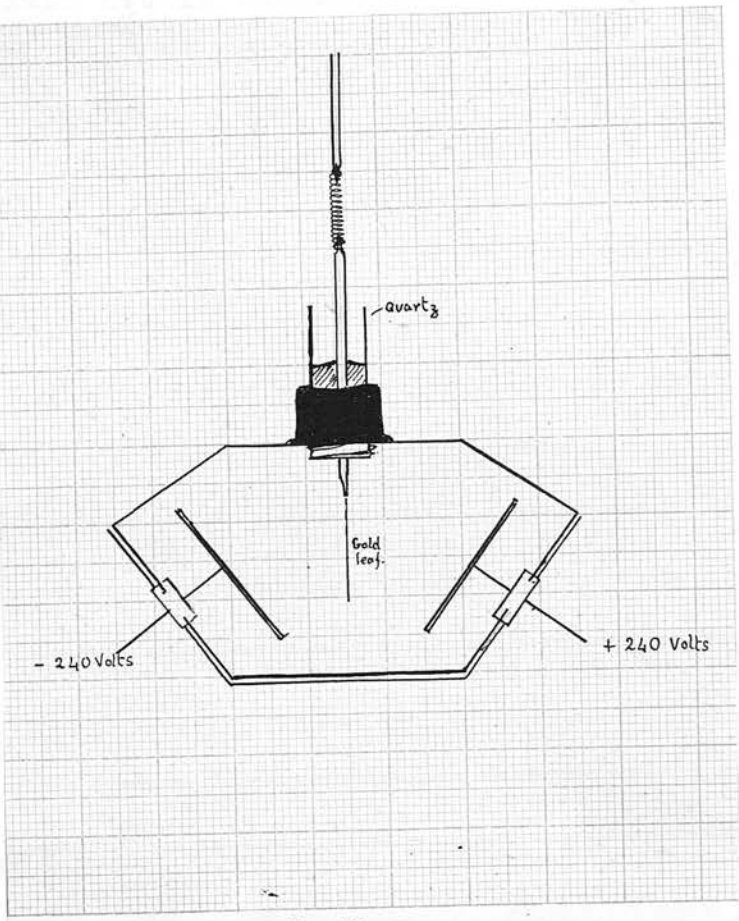


Fig. 25

discharge of the electroscope by the negative ions reaching the electrode could then be observed by means of a low power microscope, having an eyepiece scale calibrated in 0·01 cm. divisions. In general the choice of apertures and sensitivity of the electroscopes were adjusted so as to make the deflections produced in the primary and secondary electroscopes in the same time to be of the same order and was generally about 12 to 30 divisions, depending on other experimental parameters imposed.

The secondary electroscope and its method of connection to the ionisation chamber are shown in detail in Fig. 25. The gold leaf is earthed and one of the tilted plates is maintained at a positive potential of about 200 volts by means of high tension batteries. The other tilted plate was maintained at -200 volts by another batch of high tension batteries.

The zero position of the gold leaf, hanging between the two oppositely charged plates was found to be very sensitive to temperature changes and consequently the above high tension batteries were kept thermally insulated by wrapping in cotton wool and placing them inside an earthed metal box which was further thermally insulated by placing it in saw-dust contained in a white painted wooden box.

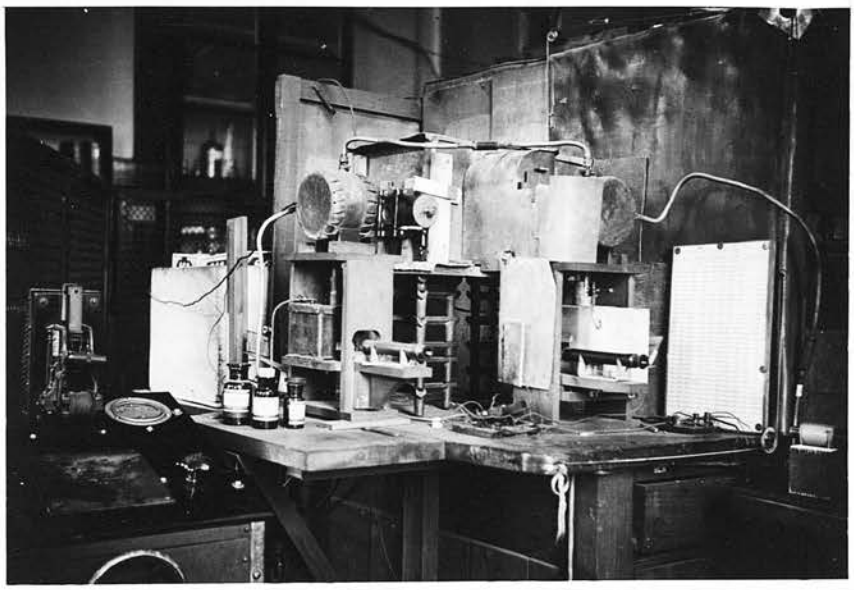
The sensitivity of the Bumstead[19] electroscope could be varied by raising or lowering the gold leaf and its support by a screw arrangement at the top of the instrument. The actual sensitivities used in this work ranged from about 4 to about 30 microscope divisions per volt for the secondary electroscope (determined by a potential dividing circuit) and

from 1 to 1·5 divisions per volt for the primary electroscope (determined by varying the potentials applied in steps of 9 volts each).

The secondary (Bumstead) electroscope was placed in an aluminium box provided with insulating sleeves through which the various lead-ins were passed. This electroscope was also mounted vertically below the secondary ionisation and protected from stray radiations by suitably placed lead screens. The electroscope electrode passing through a quartz insulator was connected to the ionisation chamber electrode by means of a light, coiled brass spring. The latter electrode was fitted with a small brass projection having a rounded tip which served to make contact with an earthing handle supported by and passing through a horizontal, covered, slit in the guard ring-tube which again was made so as to cover the whole electrode system.

The outer casing of the secondary ionisation chamber was mounted on a wooden platform having 'micanite' insulators and maintained at a constant negative potential of 240 volts by means of a batch of dry batteries. Its electrode, and consequently the gold leaf were earthed, thereby again producing a potential gradient between the electrode and the case of the ionisation chamber, so that if the gold leaf is insulated by turning the earthing handle, negative ions reaching the electrode will deflect the gold leaf towards the positively charged plate of the electroscope.

Preliminary experiments showed that a potential difference of 70 volts between the electrode and case of the larger



ionisation chamber was sufficient to give full saturation of the ionic current, but for safety the potential difference was maintained at about 240 volts.

Sulphur dioxide gas at atmospheric pressure was used in the ionisation chambers to increase the ionic current produced by a given beam of radiation. The gas was released under its own vapour pressure from syphons and passed through a drying tube containing calcium chloride granules and was then led by means of lead tubing, separated into appropriate segments by small ebonite insulating connectors, to the secondary ionisation chamber through a brass gas tap, and thence through more tubing to a gas tap on the primary ionisation chamber and thence to a water suction pump.

When filled with SO_2 after passing a steady stream of the gas through the system for about 20 minutes, the gas enclosed by the two ionisation chambers and the short tubing connecting them is isolated by turning off the appropriate gas taps but leaving the interconnecting taps open so as to ensure that gas pressures in the two ionisation chambers are always the same.

The ionisation chambers are regularly filled with fresh SO_2 at intervals of about a month or as required.

A photograph of the complete apparatus is shown on the opposite page.

(5) The High Tension Generators.

The results reported below were all obtained with the use of a Greinaher Voltage Doubling circuit, in the form of

what is generally known as a 'Constant High Tension Apparatus'. The fundamental circuit is shown in Fig. 27.

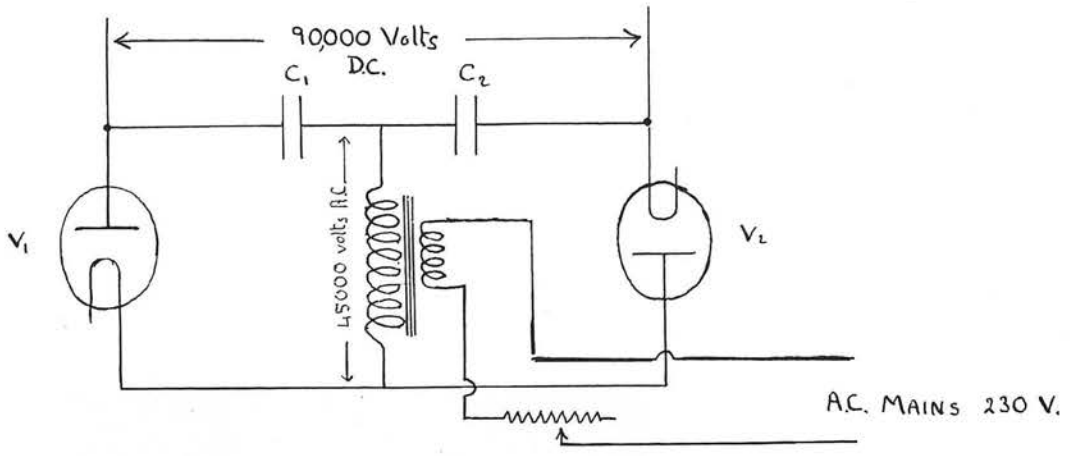


Fig 27.

The principle involved is that of charging two condensers in parallel and discharging them in series through the X-ray tube, the appropriate conditions for charging and discharging the condensers being provided by rectifying valves which are used for rectifying the A.C. output of the high tension transformer, the input voltage applied to this transformer being controlled from a switch board panel by means of a system of rheostats.

The complete Constant High Tension unit used (designed and built by Messrs. Watson's Electro Medical Co. Ltd.) is shown in Figs. 27 and 28. (over)

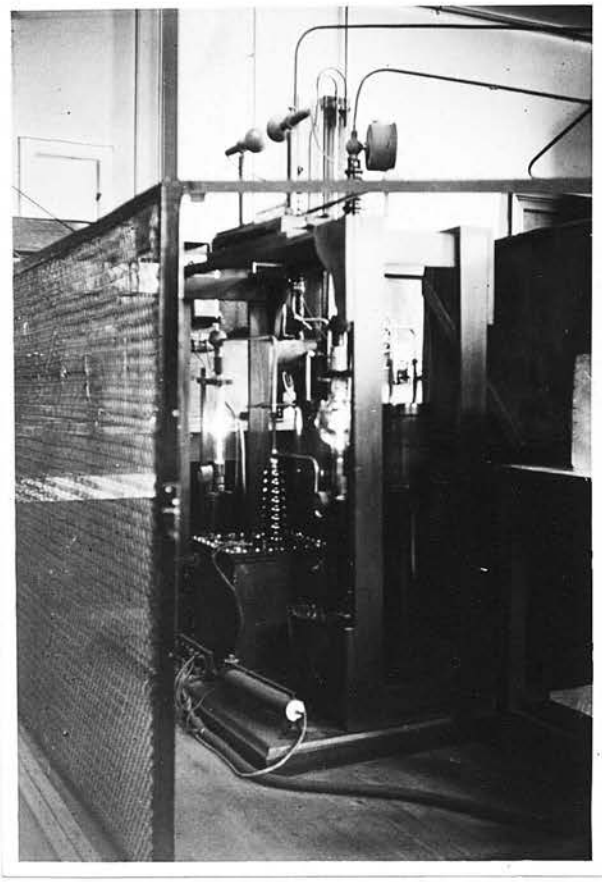


Fig. 28.

Some attempt was made to use gas tubes excited by induction coils, but owing to the lack of control in the speed of the interrupter and hardness of the tubes, the results were so irregular as to be unworthy of report and the experiments were

soon abandoned in favour of the hot cathode (Coolidge) tubes excited by means of the constant high tension apparatus, described above.

(6) The X-ray Tubes.

The experiments reported below were made with various makes and types of tubes, the individual characteristics of which are briefly given herewith.

(1) Tube No. X.P. - 3

Made by : Coolidge U.S.A.

Type : Hot Cathode, Tungsten target.

Rating : Max. Voltage 90 Kilo Volts.

(for continuous running) Max. current 2·0 milliamps.

Structural details: This tube was fitted with a cylindrical glass envelope, part of which facing the focal spot was ground very thin so as to act as a transparent window for the emerging X-ray beam. The target face was inclined at an angle of 71° to the axis of the tube. Fins were provided for cooling purposes.

(2) Tube No. 273117

Made by : Muller, Germany.

Type : Hot cathode, Tungsten target.

Rating Max. Voltage 100 Kv.

(for continuous running) Max. Current 3·0 m.a.

Structural details: This tube was fitted with an all glass envelope having a bulb in its middle;

no special 'window' arrangement was provided, the radiation simply penetrating the glass walls of the bulb.

The target face was inclined at an angle of about 71° to the axis of the tube.

This tube was fitted with a water cooling system.

(3) Tube No. 342177

Made by : Philips, Holland.

Type : Hot cathode, Tungsten target.

Rating (for contin. running): Max voltage 100 Kv. 2·5 Kilo-watt tube.

Structural Details : This tube was of the modern Metalix design, the principles of which are shown in Fig. 29.

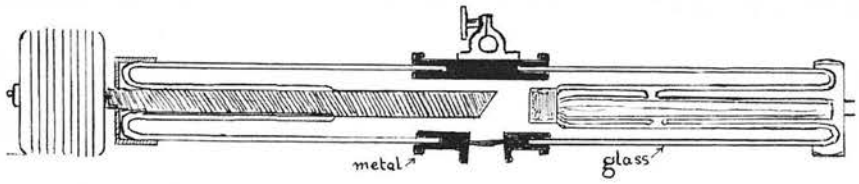


Fig 29.

The radiation emerged from a glass window inserted into the metal mid-piece which also carried a clamping device whereby the tube

could be clamped, at the desired height, on to a vertical insulated rod of mild steel.

For the proper focussing of the electron stream in this type of tube, it is imperative that the central metal piece and its supporting rod are well insulated, as otherwise the operation of the tube is erratic. The necessary insulation was achieved by placing small 'Distrene' washers under the platform on to which the central supporting rod was screwed.

The tube being of the Metalix type, it was impossible to ascertain the inclination of the target face to the axis.

After obtaining somewhat strange results with this tube, it was discovered that it possessed two distinct focal spots; the relative intensities of the X-rays emitted from these focal spots depended on the current passing through the tube.

In view of this, the experimental results obtained with this tube were scrapped and are not reported in this paper.

(4) Tube No. 43712

Made by : Coolidge, U.S.A.

Type : Hot cathode; Molybdenum target. (original Coolidge 'Helium filled' type)

Rating (for continuous running) : Uncertain, but apparently could not be used at voltages higher than 86 Kv.

Structural Details : This tube had an all glass bulb envelope; no special 'window' was fitted and no cooling arrangements were provided.

The molybdenum target face was inclined at an angle of about 88° to the axis of the tube. and was slightly convex outwards.

Owing to its various limitations, this tube was only used for a very short time for comparing the effects produced by Molybdenum targets with those produced by Tungsten target tubes.

(5) Tube No. 15291.

Made by : Philips, Holland.

Type : Metalix, hot cathode, Tungsten target.

Rating (for continuous running) : Uncertain. Probably 100 Kv. max.

Structural Details : This tube was of the 'Metalix' type alteady described for Tube No. 342177 above; it was fitted with a soda glass bulbous window, and water cooled.

The inclination of the target face to the axis of the tube was uncertain.

(6) Tube No. 433917.

Made by	:	Cuthbert Andrews, London, England.
Type	:	Hot cathode, Tungsten target, 'Therapex' tube.
Rating (for continuous running)	:	Maximum Voltage 110 Kv. Maximum Current 4·0 m.a.
Structural Details	:	This tube was very similar to the 'Metalix' tubes described above, and the same insulating precautions were taken. The tube was fitted with a bulbous soda-glass window and was water cooled. The angle of inclination of the target face to the axis of the tube was uncertain but, being a modern tube, was probably of the order of 71°.

This tube was brand new and as such the results obtained with it are probably particularly reliable.

EXPERIMENTAL PROCEDURE AND RECORD OR RESULTS.

Procedure and Manipulation.

Before commencing a series of observations and when the apparatus was not in actual use, the electrode and gold leaf of the primary electroscope was connected through a high resistance to the positive terminal of a battery having a potential difference of about 240 volts, the negative terminal of which was earthed.

The electrode and gold leaf of the secondary electroscope were connected to earth through the earthing lever inserted through the guard ring.

When readings were taken, the primary electroscope was left connected to the battery. The secondary gold leaf was disconnected from earth and the shutter S' (Fig. 16, 17,) was raised; the secondary gold leaf thus gained an ionic charge and gradually moved towards one of the tilted plates of the electroscope. This movement was watched through the microscope and when one sharply focussed edge of the image of the gold leaf appeared to coincide with some convenient microscope scale division, the shutter was quickly lowered and the primary gold leaf disconnected from the battery and insulated. The position of the sharply focussed edge of the primary gold leaf relative to the primary microscope scale was accurately read to the nearest 0·1 of a scale division, (in some cases it was possible to estimate this reading to 0·05 of a microscope division) and recorded as microscope reading P_1. The shutter S was then raised, and the movement

of the sharply focussed edge of the secondary gold leaf over the microscope scale was watched until it had traversed a convenient range of between 12 to 20 microscope scale divisions and again appeared to be in coincidence with a definite microscope scale division, when the shutter was again quickly lowered and the position of the sharply focussed edge of the primary gold leaf relative to its microscope scale was carefully read to the greatest possible accuracy (0·1 or 0·05 of a scale division) and recorded as P_2. The difference in the two primary microscope readings $P_2 - P_1$ thus gave a measure of the deflection P of the primary gold leaf corresponding to a known standard whole number of microscope divisions, secondary deflection, and the ratio of the deflections may be calculated to obtain S/P which was taken to represent the ratio of the ionisations produced by the primary and secondary beams. (Certain corrections were made to allow for the natural leaks and 'soaking in' of charge in the ionisation chambers and electroscopes.)

These corrections were somewhat difficult to evaluate but the following procedure was developed and applied throughout the work reported in this paper.

The time taken for the secondary gold leaf to travel over its standard deflection S and for the corresponding deflection P of the primary gold leaf was carefully noted and recorded as T, and after reaching the position P_2 (above) the gold leaves were left in their deflected positions for a further time of T seconds and any leaks (positive or negative)

which occurred in either electroscope during these additional T seconds were recorded as p and s leaks respectively.

The primary gold leaf was then again charged up by connecting it to the 240 volt battery and the secondary gold leaf earthed and left in this state for a further period of 2T seconds to enable the potential gradients across the insulating plugs to return as nearly as possible to their initial states.

The secondary gold leaf was then disconnected from earth and brought up to its starting position again. The primary gold leaf was then disconnected from the battery and insulated and any deflections (positive or negative) which occurred in a further time interval of T seconds with the shutter down, were recorded as the natural leaks p and s.

In this way, we get two values of the primary and secondary leaks corresponding to the two positions of the gold leaves, i.e. at the beginning and end of the deflection range.

The average values of the primary and secondary leaks were then calculated with due regard to their algebraic signs and the appropriate corrections applied to the mean of at least two observed values of the deflections P and S, and the resulting value of S/P was plotted against the variable parameter.

In actual practice the primary leaks were generally very small, $\pm$ 0·1 microscope divisions per hour, whereas the secondary leaks were considerably greater owing to the much greater sensitivity of the electroscope and ranged between about 3 to 1 division per hour with Sulphur Dioxide in the ionisation

chambers and between about 0·2 to 0·1 divisions per hour with air (at atmospheric pressure) in the ionisation chambers.

The Possible Error in the Determination of the Ionisation Ratio S/P.

The absolute evaluation of the maximum possible error in this type of experiment is extremely difficult, in view of the uncertainties involved in estimating leak corrections, the small but finite filtering of the radiation through the lead screens and the fairly rough control of the voltage applied across the X-ray tube, so that all that can be attempted at present is to evaluate the observational error.

When the ionisation ratio S/P was evaluated as described above, a large number of times under conditions which were kept as constant as possible, it was noticed that the deviations of the individual values of the ratio S/P from the mean value was never greater than one per cent except in certain cases where the ratio was measured at or near a 'J' discontinuity as has already been mentioned. In every case, when the apparatus was in good working order and no strong winds or sudden temperature changes prevailed, the ratios S/P measured in regions remote from a 'J' discontinuity were found to be constant to within one per cent and this was therefore taken as the intrinsic possible error in the experiment.

The current through the X-ray tube was measured on a 0 - 5 m.a. milliameter and never exceeded 3·0 m.a. The actual current through the tube was difficult to measure exactly owing to unstable brush discharges.

The potential differences across the tube were measured,

by means of a standard calibrated spark gap, and its relation to the voltage applied across the primary coil of the transformer was recorded for various tube currents.

EXPERIMENTAL RESULTS.

The Filtering Experiment.

A typical result of this type of experiment obtained by the writer using a Paraffin Wax scatterer 19 m.m. in thickness, with a potential difference of 60 Kv maintained across a Coolidge X.P-3 tube is shown in Fig. 30.

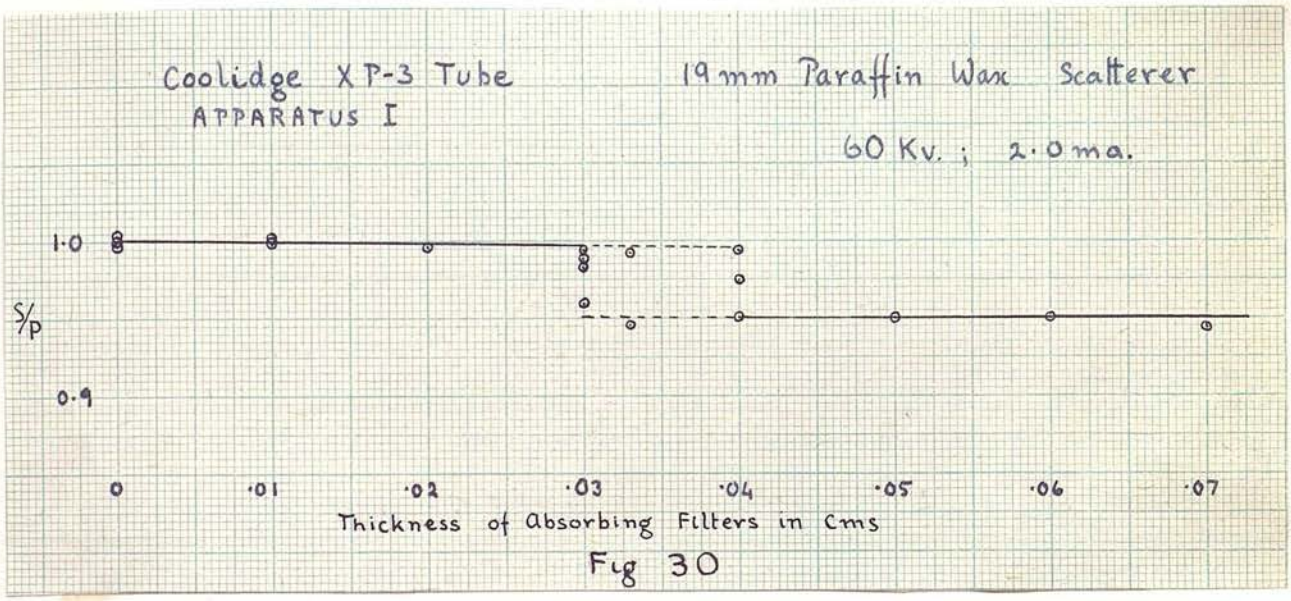


Fig 30

The result is immediately seen to be quite different from what was expected from either the Photon or Classical theory of scattering of X-radiation as discussed under the heading 'Principles of the Experiments' on pages 26-42.

The experimental curve is seen to consist of two distinct levels for each of which the ionisation ratio S/P appears to have definite and almost constant values. The two levels are separated from one another by a region where the value of the ionisation ratio S/P shows a marked fluctuation, repeated determinations of S/P in this region sometimes varying from one another by as much as 5%. And yet, for thinner or thicker filters inserted in the primary and secondary beams, the variation of the repeated determinations of S/P was never

greater than 1°/o. The result seems to lead to the following interpretation.

As the thicknesses of aluminium filters inserted in the paths of the primary and secondary beams is gradually increased up to a critical thickness of about 0·03 cms. the ionisation ratio $^{S}/_{P}$ remained almost constant, but when the critical thickness of 0·03 cms. is reached, the value of $^{S}/_{P}$ on repeated determinations appears to have any value intermediate between two definite values, limited on the upper side by the value of the ratio $^{S}/_{P}$ before the critical thickness was reached and on the lower side by a new lower value of $^{S}/_{P}$.

As the thickness of the filter is still further increased to 0·033, 0·035, 0·04 cms. the fluctuation in the value of the ionisation ratio is found to persist, although as the thickness increases, there is a marked probability of getting a lower value of $^{S}/_{P}$. If the thickness of the filter is still further increased to 0·05, 0·06 and 0·07 cms. the value of the ratio $^{S}/_{P}$ is once again found to be constant to within 1°/o, but is now found to be at the lower value corresponding to the lower limit observed in the fluctuating region.

It thus appears that for small thicknesses of filtering Aluminium, the primary and secondary beams are equally absorbable, until a certain critical thickness of filter is reached, when apparently some transformation occurs in either or both beams so that the ionisation ratio $^{S}/_{P}$ is reduced and then for additional thicknesses of filters the ratio is again constant, apparently indicating that the

primary and secondary beams are again almost equally absorbable, - at least for thicknesses of filter up to 0·07 cms. of Aluminium and possibly more.

This type of result is in full confirmation with the results of similar experiments obtained by previous workers in this laboratory. The region at which the fluctuation in the ionisation ratio S/P is most marked has been called the 'J' discontinuity, and appears to be associated with a 'J transformation' of the properties of either the scattered or transmitted radiation after passing through a critical thickness of Aluminium filter.

Before a theoretical explanation of the 'J transformation' can be obtained, a thorough experimental investigation of the properties of the 'J transformation' region must be carried out with the aim of determining which, if any, of the experimental parameters affect its properties, and the way in which these parameters affect it.

Properties of the 'J. Discontinuities'.

It appears at first sight that the horizontality of the "S/p-thickness of filter" curve and the regions of the discontinuities might be due to unevenness of the Aluminium filtering sheets, but this cannot be the case because during the experiment the filters used in the primary and secondary beams were always interchanged and no corresponding change in the value of S/P was observed. As a further test for this, the filtering experiment was repeated using a completely new set of fresh Aluminium filters, and the result obtained is shown in Fig. 31, where it is seen that the

'J-discontinuity' region again appears at the same thickness of filtering aluminium.

The result shown in Fig. 31 also reveals

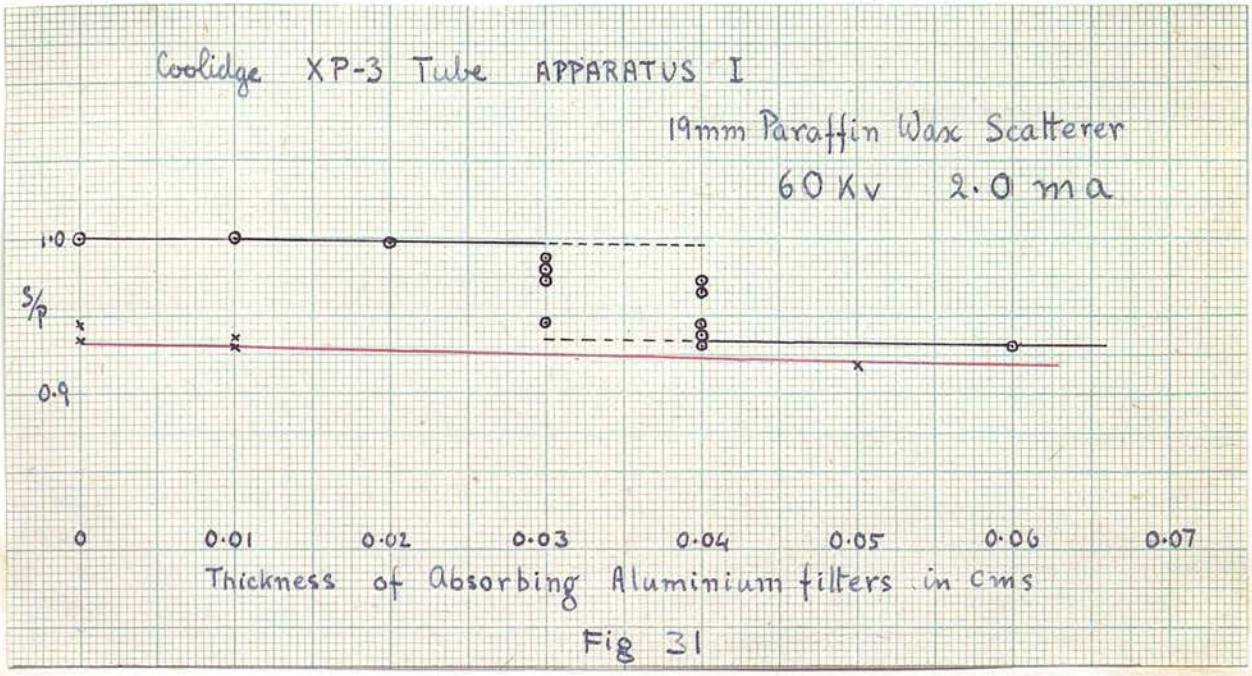


Fig 31

another striking fact, the curve shown im black ink showing that a 'J-discontinuity' was obtained in the morning. The tube was switched off for a period of one and a half hours, and the experiment repeated in the afternoon. The result is shown in red ink in Fig. 31. The remarkable feature of this result is that no 'J-discontinuity' is observed and the ratio S/P is practically constant for a range of filter from 0 to 0·05 cms. in thickness.

In fact, this latter result seems to suggest that the position of the 'J-discontinuity' has been shifted considerably to the left, leaving us an almost constant value of S/P having a magnitude corresponding to the lower level of the morning experiment.

The morning and afternoon results were obtained under apparently identical experimental conditions, and seem to show that the appearance or non-appearance of the 'J-discontinuity' was associated with a marked shift in the position or critical thickness at which the discontinuity appears and that the shift occurred although the same filters, scatterer, apertures, X-ray tube, current and voltage were used in the two cases.

Additional confirmation of the shift of the 'J-discontinuity' was obtained in another experiment carried out under apparently identical conditions to the above, the result of which is shown in Fig. 32.

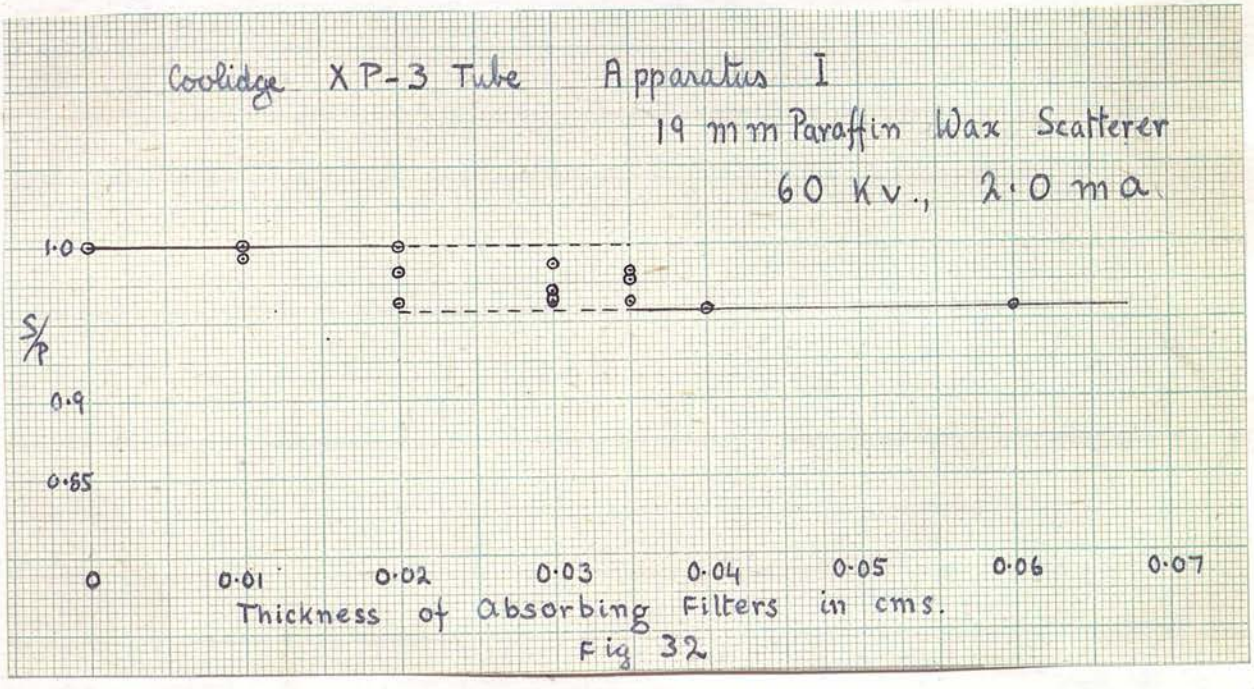


Fig 32

It is seen that in this case the fluctuation in the value of S/P occurs when the thickness of the filter is 0·02 cms. of Aluminium, as compared to the thickness of 0·03 cms. in the results of Figs. 30 and 31.

A noticeable 'spread' of the fluctuation region is also seen, together with a slight decrease in the actual drop in

the ratio.

The effect of changing the potential difference across the tube was then tried. The result obtained with a potential difference of 80 Kv. across the tube is shown in Fig. 33.

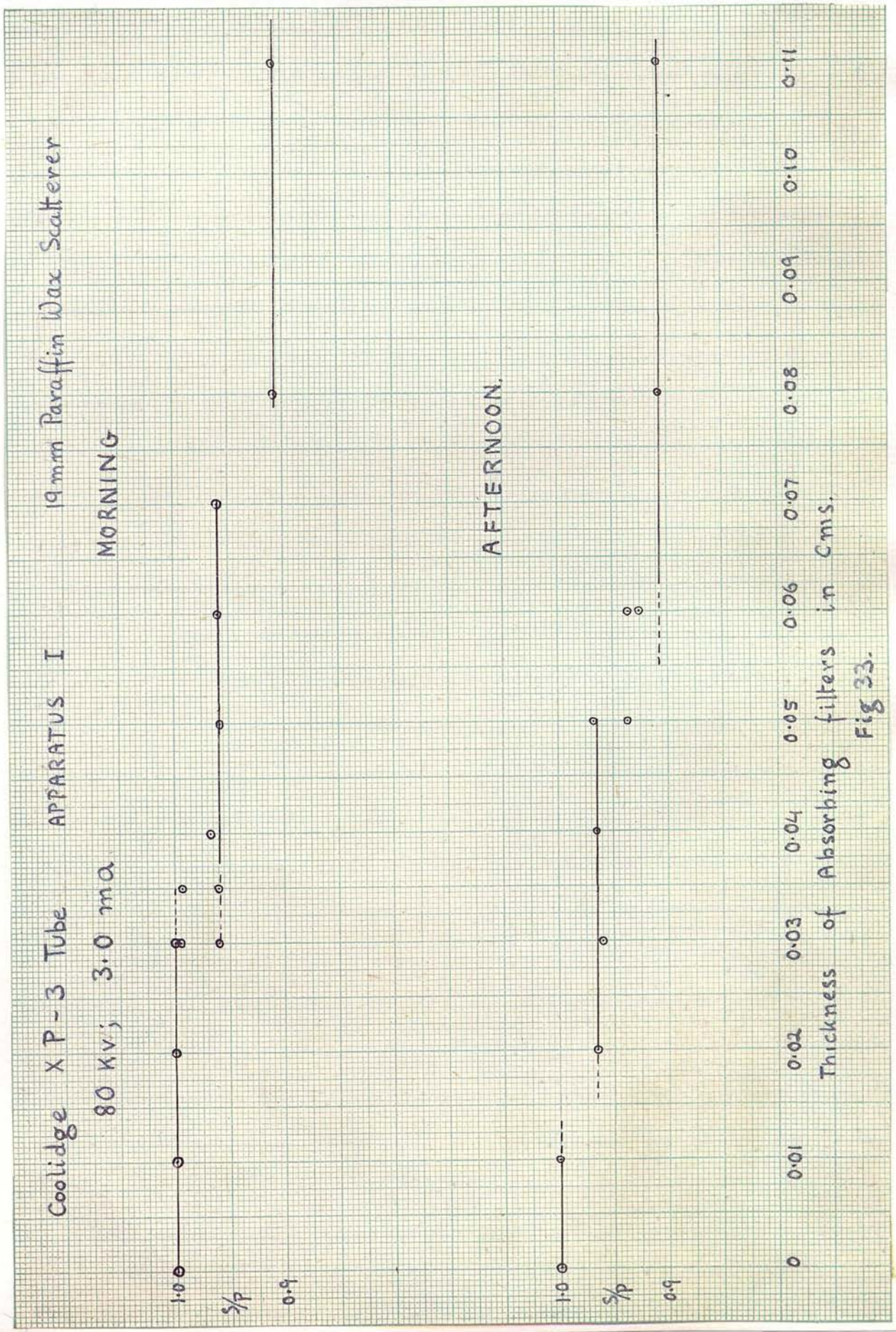


Fig 33.

No marked change in the position of the 'J discontinuity' is apparent in this case, but by extending the thickness of the filters used up to 0·11 cms. of Aluminium, another 'J discontinuity' appears at a critical thickness of about 0·07 cms. of Aluminium. Here again experiments done under what seemed like identical conditions in the morning and afternoon of the same day showed a marked shift of the 'position' of J discontinuities to smaller critical thicknesses of the filters in the afternoon result.

The experiment with 80 Kv across the tube was repeated several times, and the position or critical thickness at which the J discontinuity occurred was found to fluctuate to a certain extent although all the known conditions seemed to be identical in every case.

The actual type of curve obtained also seemed to vary between the types described above and the type shown in Figs. 34 and 35.

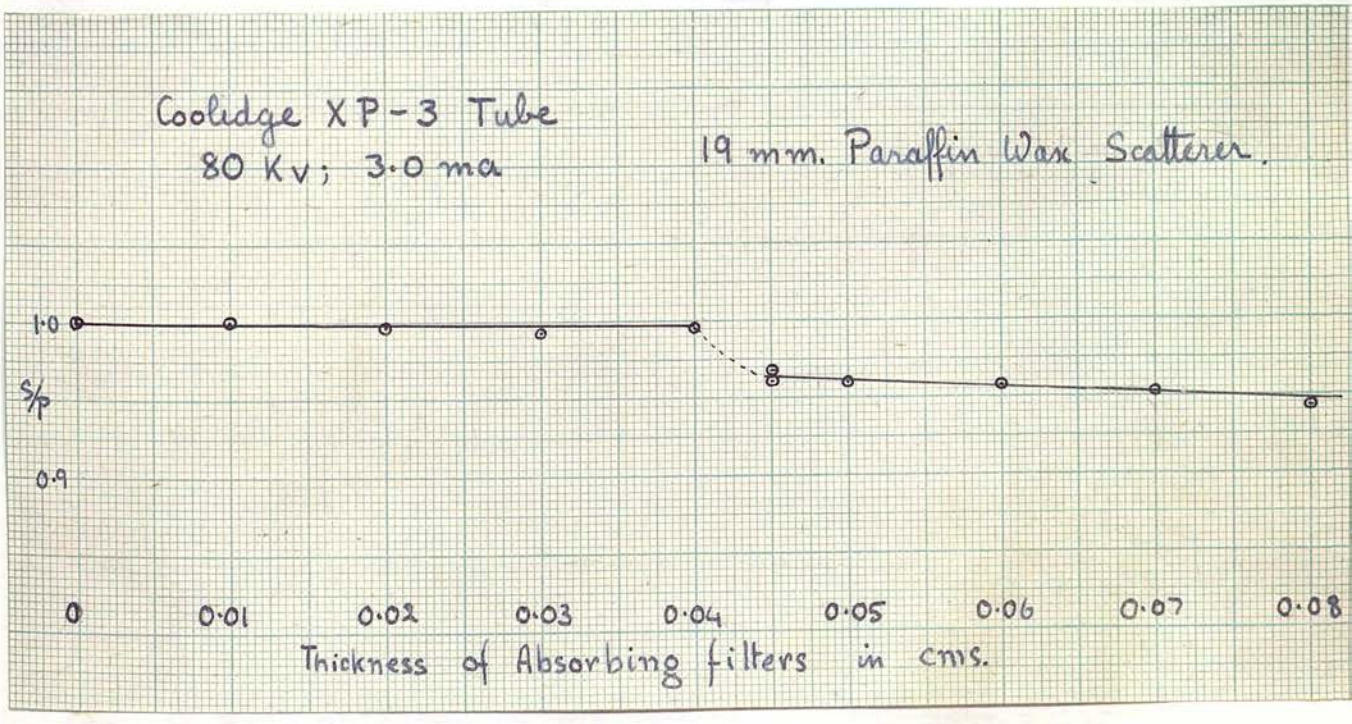


Fig 34.

This curve seems to be characterised by an almost constant value of the ionisation ratio S/P for filter thicknesses varying from 0 to 0·04 cms. of aluminium, after which a J discontinuity takes place with a sudden drop in the value of the ratio S/P followed by a sloping curve, apparently indicating that the secondary beam is now markedly more absorbable than the transmitted beam.

An attempt to correlate this type of curve with the one showing the short sharp J discontinuities described above will be made when we discuss the results obtained.

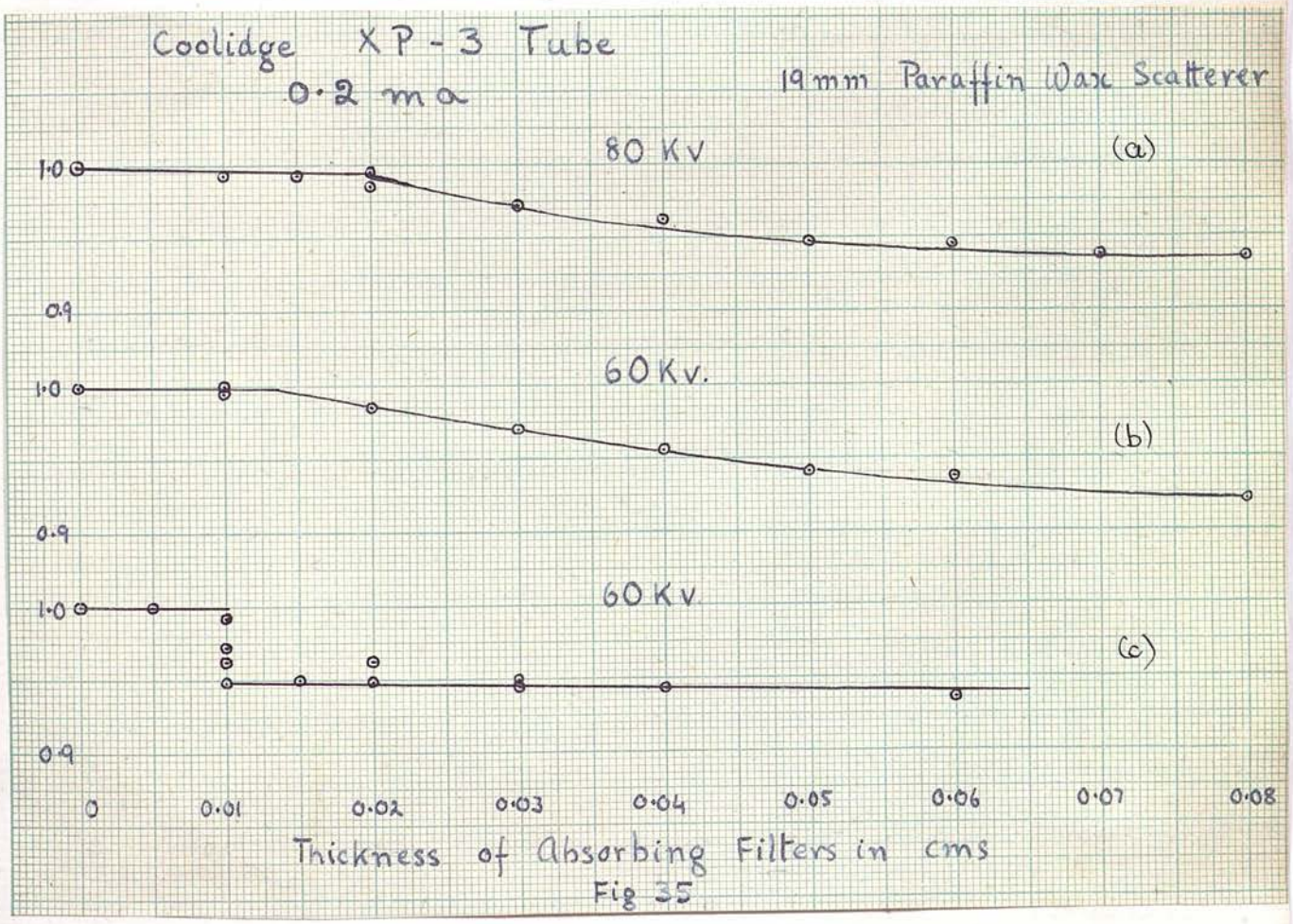


Fig 35

As shown in Fig. 35, the J-discontinuity described above is in some cases replaced by a sudden change in the slope of the curve. For example, the two 60 Kv. curves shown in Fig. 35 were obtained on the same day under apparently identical conditions.

In spite of the instability of the 'J discontinuity' as described above, on some occasions the discontinuity appeared to be quite stable and in these cases experimental investigation of the effect of changing the voltage across the tube on the position and type of discontinuity produced could be investigated with a fair degree of accuracy.

The results of such experiments are shown in Fig. 36.

It appears that the J discontinuity is shifted to the right as the voltage across the tube is raised. From this we may conclude that as the general radiation emitted by the tube is hardened by raising the potential difference across the tube, the critical thickness of Aluminium filter required to produce the J discontinuity increases.

This conclusion could be tested experimentally in a different manner; the potential across the tube was kept constant but the hardness of the radiation falling on the scatterer was varied by placing various thicknesses of Aluminium filters between the X-ray tube and the scatterer.

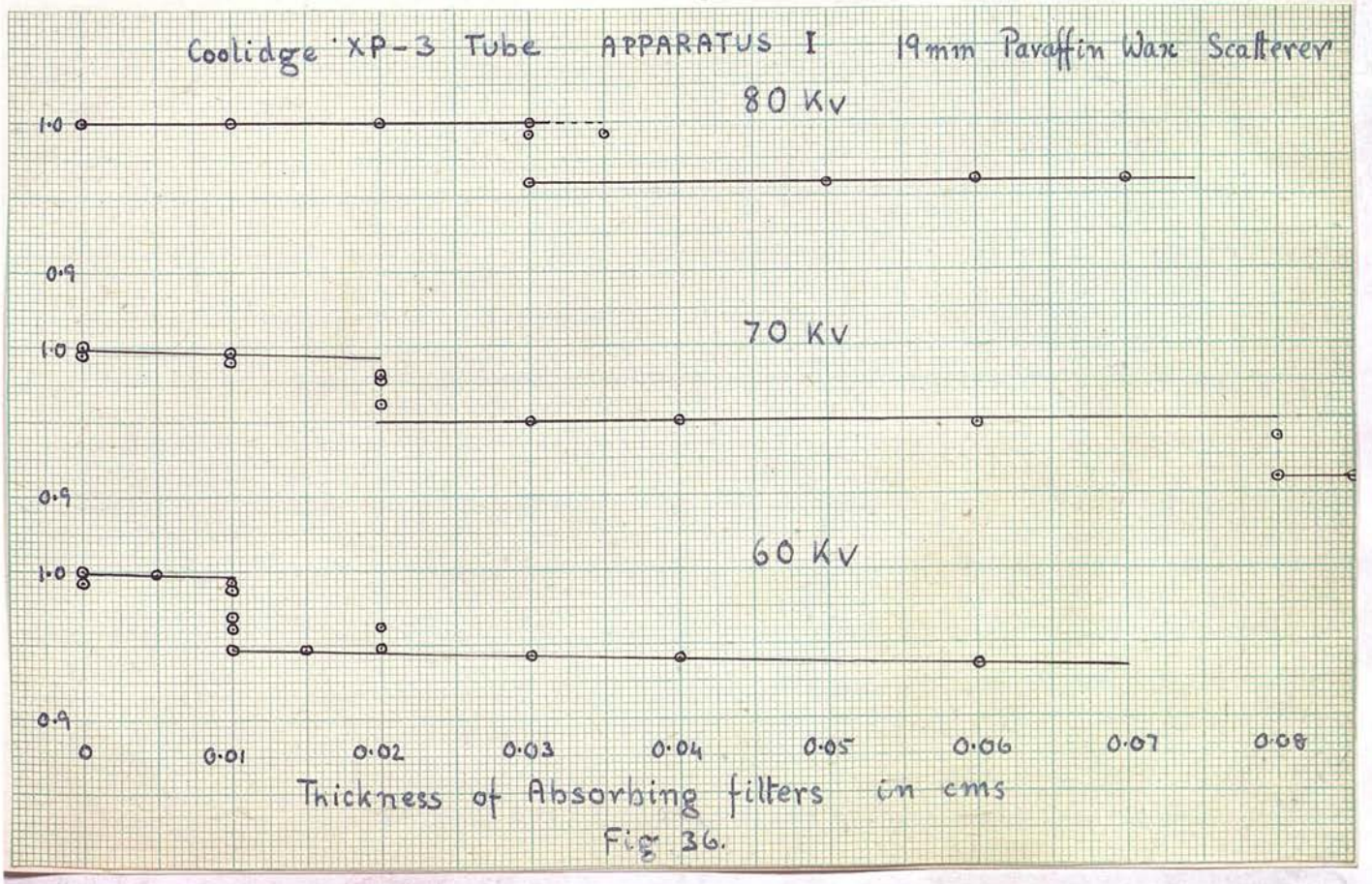


Fig 36.

In practice, it was found that a Paraffin Wax Scatterer, 11 mm. in thickness also showed J-discontinuities, and that these discontinuities seemed to be much more stable in position than the corresponding discontinuities obtained with the thicker 19 mm. Paraffin Wax Scatterer. Fig. 37 shows the variation of the critical thickness of Aluminium filters placed in the primary and secondary beams required to produce a J discontinuity with various thicknesses of Aluminium filters inserted between the scatterer and the X-ray tube.

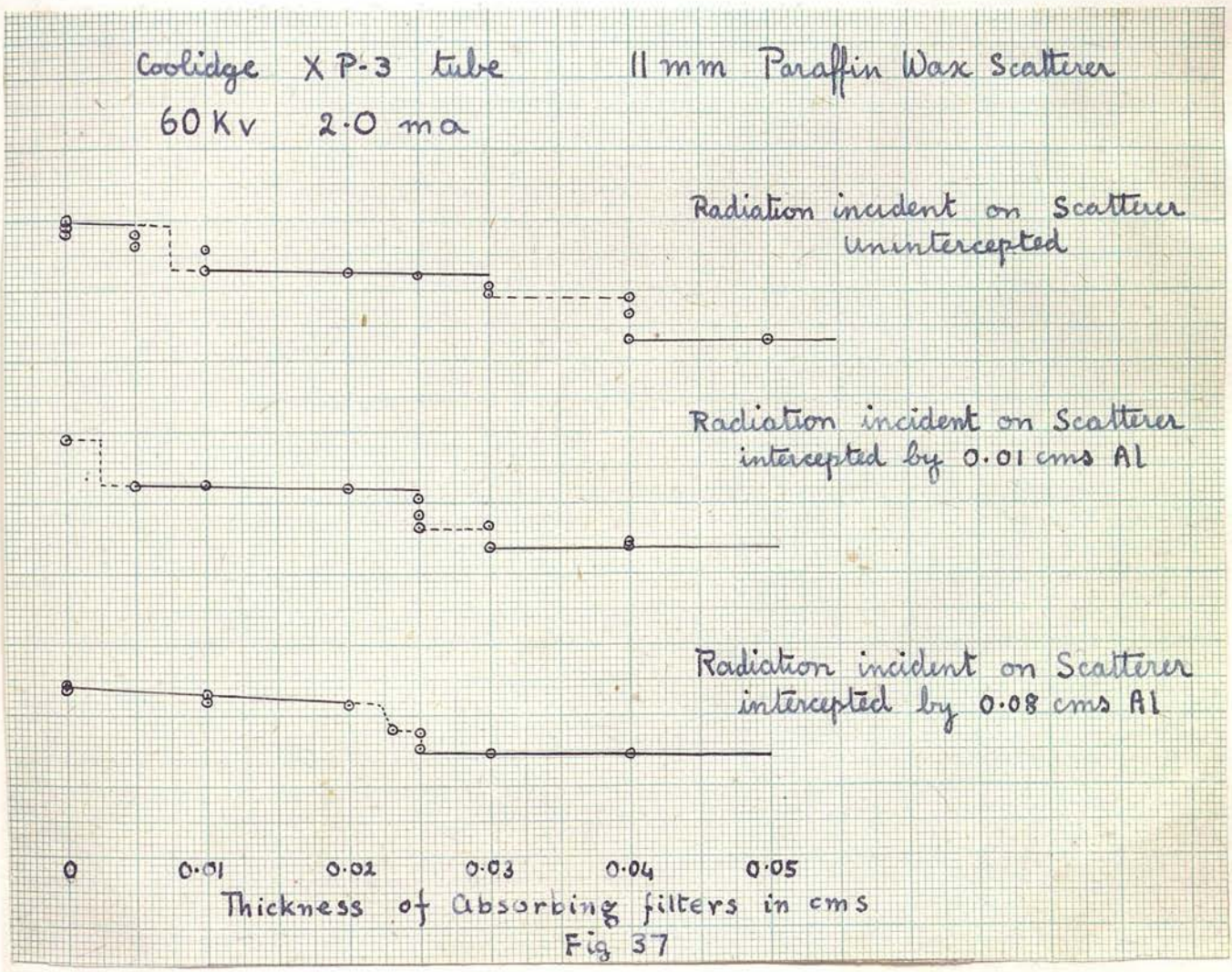


Fig 37

The curves shown in Fig. 37 show a distinct shift of the J-discontinuity to the left as the pre-scatterer filter thickness is increased. It should be noted that the values of $^{S}/_{P}$ for

each of the horizontal or nearly horizontal levels in the curves do not seem to be affected by the insertion of filters between the scatterer and the X-ray tube, but when the thickness of this latter filter is sufficiently thick, the shift of the first 'J discontinuity' to the left is so great that it disappears from the graph, and this disappearance is associated with a marked decrease in the value of S/P when no filters are present in the Primary and Secondary beams. This fact in itself gives strong support to the fundamentality of the 'J discontinuities'.

The results shown in Fig. 37 are in a way very extraordinary and unexpected, because as we have seen in Fig. 36, hardening the radiation incident on the scatterer by increasing the voltage across the tube tended to shift the 'J discontinuities' to the right, i.e. to thicker critical thicknesses of primary and secondary filters. On the other hand, if the incident radiation is hardened by passing it through filters of Aluminium, the greater the thickness of the filter, the greater is the shift of the 'J discontinuity' to the left, i.e. to thinner critical thicknesses of primary and secondary filters.

In other words, these experiments seem to show a marked difference in the properties of the 'J discontinuities' produced by hardening the radiation by increasing the voltage across the tube, compared with hardening by filtering before scattering.

A thorough investigation of the properties of the discontinuities and their dependence on various experimental

parameters could not be carried out with the Coolidge X.P.-3 tube used throughout the experiments described above, because as time went on the discontinuities became scarcer and scarcer and eventually were replaced by curves such as are shown in (g) Fig. 38, and finally by those closely approximating the exponential curve predicted by the Quantum theory as discussed on page .

Every attempt to obtain discontinuities by varying the current, voltage across the tube, apertures and thicknesses of scatterers used did not produce any definite discontinuities, and during these experiments a puncture developed in the thin glass window of the tube.

As a summary of the results obtained with the Coolidge X.P.-3 tube, we can only state that the tube was not in use for several months before the writer commenced the experiments described above, and then showed marked discontinuities which seemed to be undoubtedly genuine fundamental effects and not in any way associated with observational error or faulty technique.

Gradually with use the discontinuities were sometimes replaced by curves showing short horizontal lines followed by a roughly exponential curve as shown in Fig. 35 (b).

Gradually this type of curve completely replaced the discontinuities, and eventually even the short horizontal section also disappeared, leaving only the roughly exponential type of curve.

It thus seems that there are certain factors pertaining to the X-ray tube which govern the appearance or non-appearance of the discontinuity, and that a long interval of

rest of the tube preceding the experiments is somehow favourable to the appearance of the 'J discontinuities'. This 'rest effect' has also been noticed by other workers in this laboratory.

The gradual deterioration of the discontinuities is shown in Figs. 38 and 39.

After some months, the 'J discontinuities' seemed to disappear completely and were replaced by the short horizontal portions followed by the roughly exponential curve, and in fact, even these short horizontal sections did not always appear. It must, however, be emphasised that when the discontinuities do appear, there can be no doubt about their existence. It had been suggested that there might be a psychological factor associated with the observer's readings. In particular, the critical thickness of filters at which a 'J discontinuity' might be expected was known from the results of previous workers, and consequently there might be a latent psychological tendency to produce an error in the readings when the discontinuities are expected. This possibility cannot, however, account for the discontinuities observed by the writer as they corresponded to abrupt changes of up to 0·8 divs. microscope in the primary microscope readings, these changes being well beyond the observational error.

Also, on some occasions when repeating an experiment which produced definite discontinuities and working under identical conditions, no discontinuities were observed.

These considerations in themselves suffice to discard a 'psychological effect' giving rise to the observed

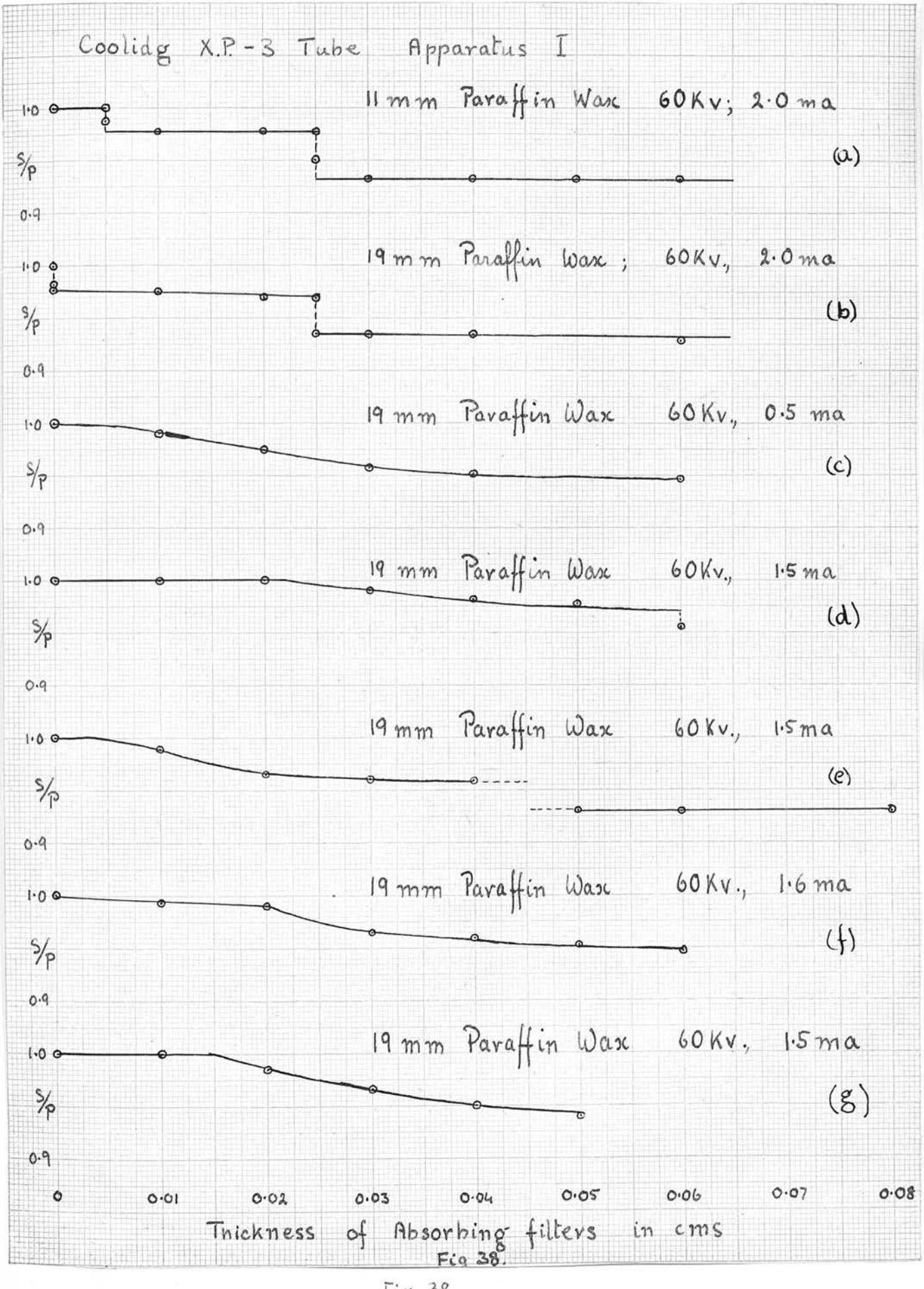

Coolidg X.P.-3 Tube Apparatus I
11 mm Paraffin Wax 60Kv; 2·0 ma
(a)
19 mm Paraffin Wax ; 60Kv., 2·0 ma
(b)
19 mm Paraffin Wax 60Kv., 0·5 ma
(c)
19 mm Paraffin Wax 60Kv., 1·5 ma
(d)
19 mm Paraffin Wax 60Kv., 1·5 ma
(e)
19 mm Paraffin Wax 60Kv., 1·6 ma
(f)
19 mm Paraffin Wax 60Kv., 1·5 ma
(g)
S/P
1·0
0·9
0
0·01
0·02
0·03
0·04
0·05
0·06
0·07
0·08
Thickness of Absorbing filters in cms

Fig 38.

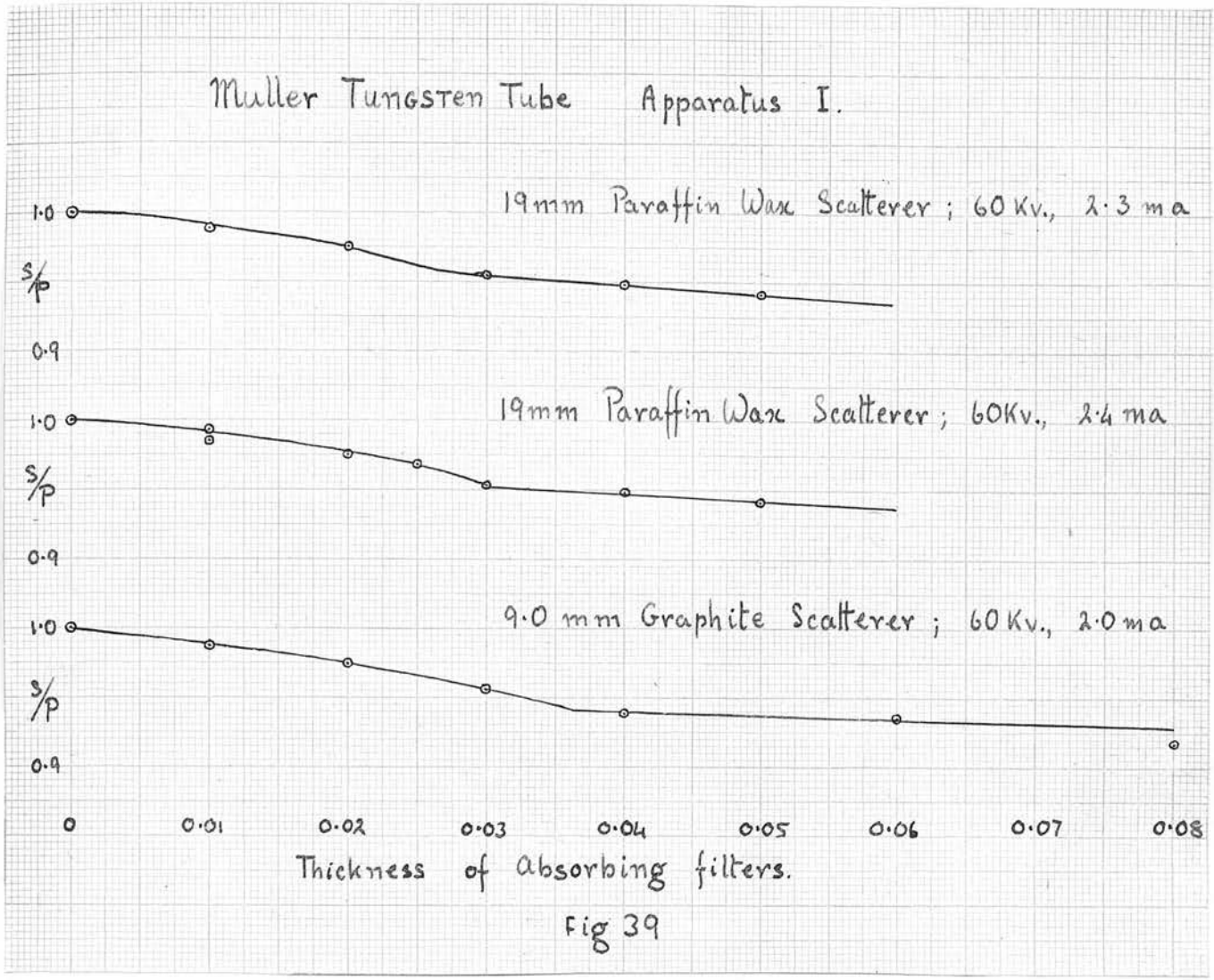


Fig 39

discontinuities, but as a further test of this possibility, the following experimental procedure was carried out.

The primary and secondary filters were made up by Mr. T. Lewis of this Department and given to the writer so that the latter did not know what the actual thicknesses of the filters were, and the values of S/p observed with sets of filters labelled Nos. 1, 2, 3, etc. were tabulated against the number of the filter, and the actual thicknesses of filters No. 1, 2, 3 ... were only obtained from Mr. Lewis

at the end of the completed experiment and the curve then plotted. The discontinuities were again found to occur at precisely the same thickness of filters as when the actual thicknesses were known during the experiment. This result seems to show quite conclusively that the discontinuities observed were not due to any psychologically induced errors of observation.

Another factor which might tend to produce constant values of S/P when thin primary and secondary filters are used is the possibility of the scatterer not being set accurately at 45° to the incident radiation, and in particular, owing to this fault it might produce a greater filtering effect on the secondary beam than on the primary beam, thereby tending to harden the secondary beam and thus masking the softening of this beam supposed to be produced by the scattering process.

With a view to testing this possibility, the scatterer was set as accurately as possible at 45° to the incident radiation (axis of the apparatus) and a curve of S/P against thickness of primary and secondary filters was plotted. (In this particular case, the curve was of the roughly exponential type shown in (a) Fig. 40.)

The experiment was then repeated after setting the scatterer well off the 45° position and then again with the scatterer still further off. The results of this experiment are shown in Fig. 40 and from these, it is easily seen that the 19 mm. scatterer has to be set at an angle of 65° to the incident beam in order to produce a horizontal, constant S/P - thickness of filter curve and as the maximum error in the

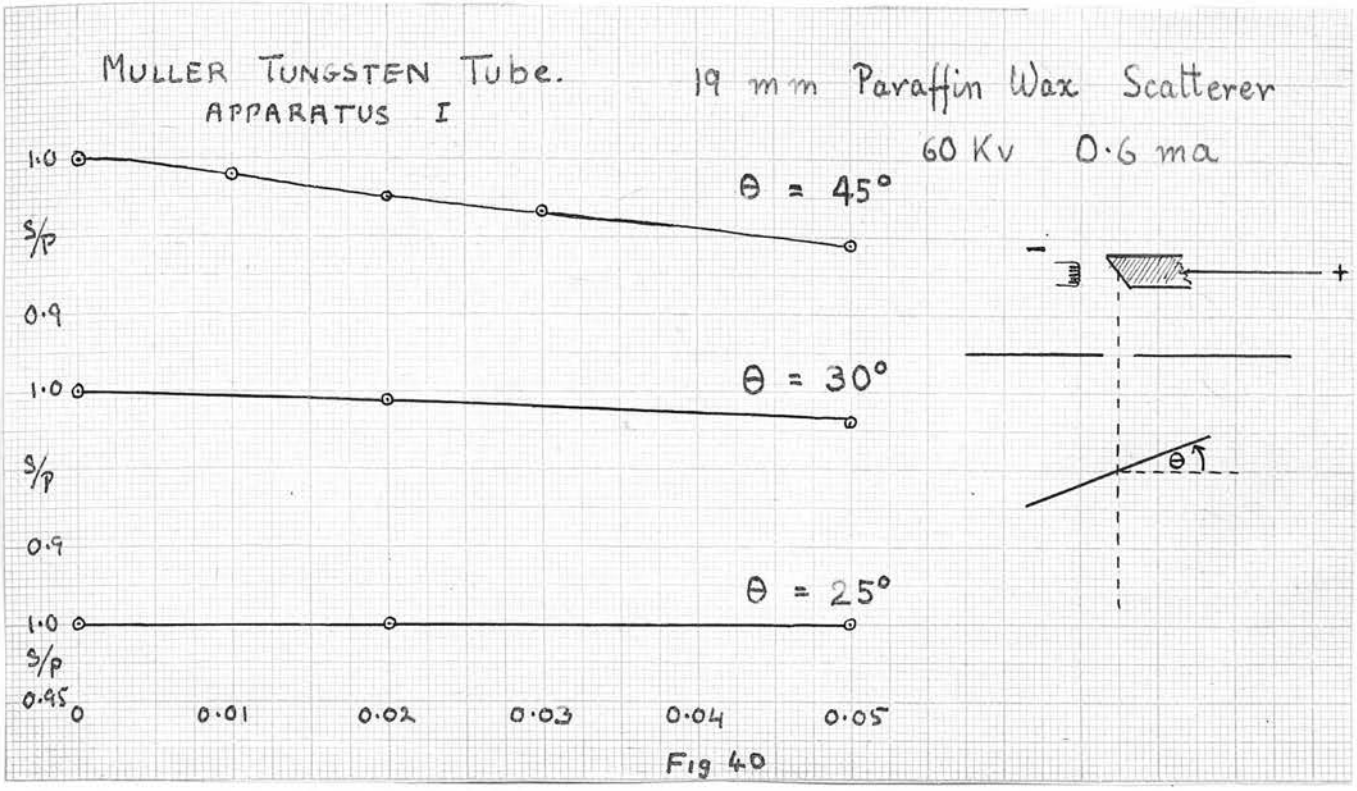
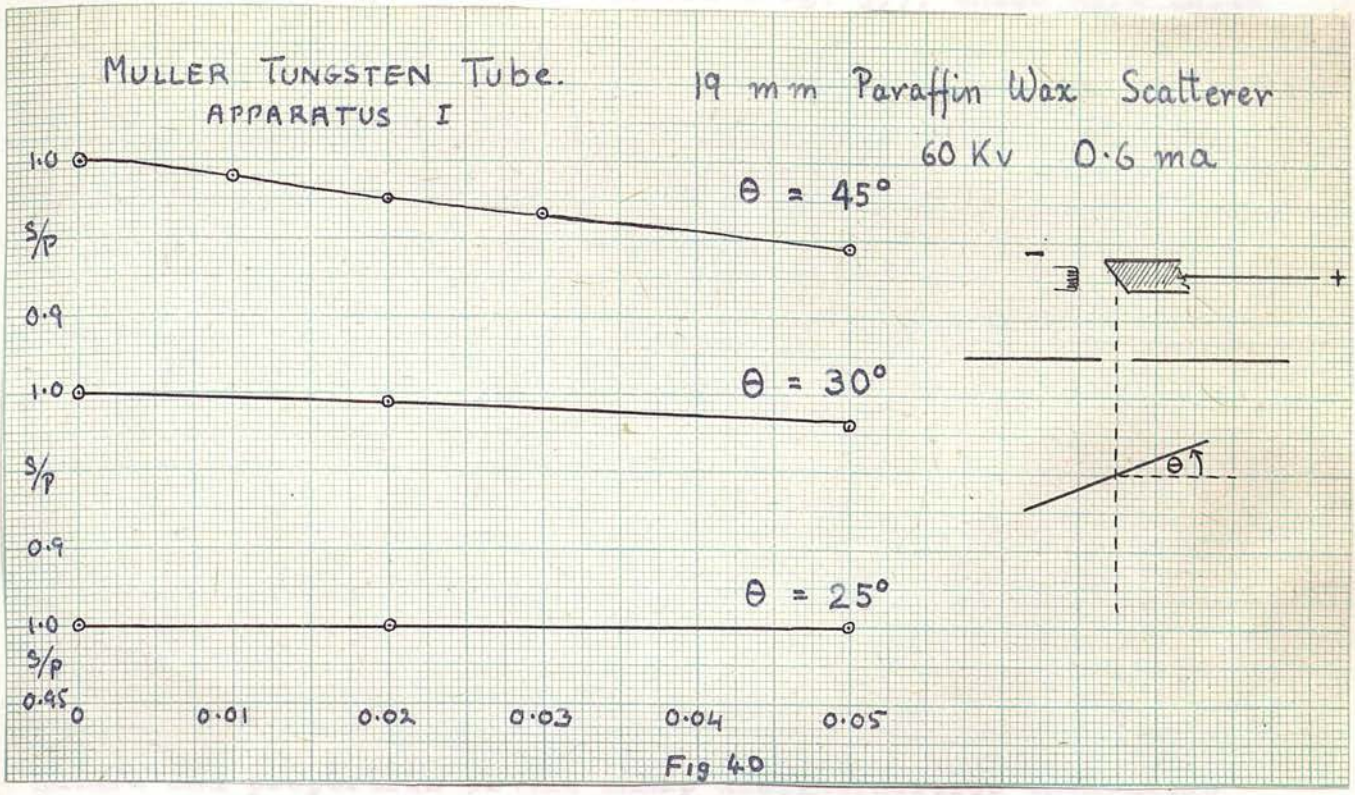


Fig 40

actual setting of the scatterer is not more than $\pm 1^{\circ}$ and the spread of the scattered beams never exceeded 10°, it is clear that the short sections of constant S/P observed with thin filters cannot be attributed to faulty adjustment of the scatterer.

A general survey of all the results obtained from the experimental investigations described above (only part of the results are reproduced here) seems to show that the 'J discontinuities', when they occurred, were of a fundamental nature and not simply spurious results. Furthermore, the appearance and type of discontinuity observed seemed to depend principally on the X-ray tube or some particular state of the tube. For example, no actual sharp discontinuities were observed with the Muller Tube No. 273117, but this tube systematically and consistently gave curves which showed



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distinct convexity for thin filters (Fig. 39), which were quite distinctly different from the concave exponential curves predicted by the Quantum theory. In fact, these convex curves appear to be identifiable with the curves showing short initial constant values of S/P, followed by a roughly exponential decline, and this in turn seems to be associated with the 'blurring' of a sharp discontinuity (see for example cases b and c, Fig. 35).

Thus the consistent type of curve obtained with the Muller tube does, indirectly, give support to the existence of the discontinuities.

The writer was particularly keen on investigating the nature and properties of the sharp discontinuities themselves, and every attempt was made to produce these discontinuities; but for a long time none were observed and eventually the search for them was abandoned in favour of another type of experiment, now generally referred to as the 'Scattering Experiment' as this type of experiment gave very consistent results. Nevertheless, every now and again the Filtering Experiment was returned to under various conditions, but with no success as far as the appearance of a sharp discontinuity was concerned, Fig. 41, until very recently when using a brand new Cuthbert Andrews Therapex tube, No. 433971, with Lithium, Beryllium Oxide and Boron Scatterers, marked discontinuities were again obtained. These scatterers seemed to be particularly favourable to the production of sharp discontinuities, as shown in Figs. 42, 43 and 44.

The discontinuities are particularly well marked with a

potential difference of 60 Kv. across the tube when a Lithium scatterer is used, and with a potential difference of 90 Kv. across the tube in the case of Boron and Beryllium Oxide scatterers.

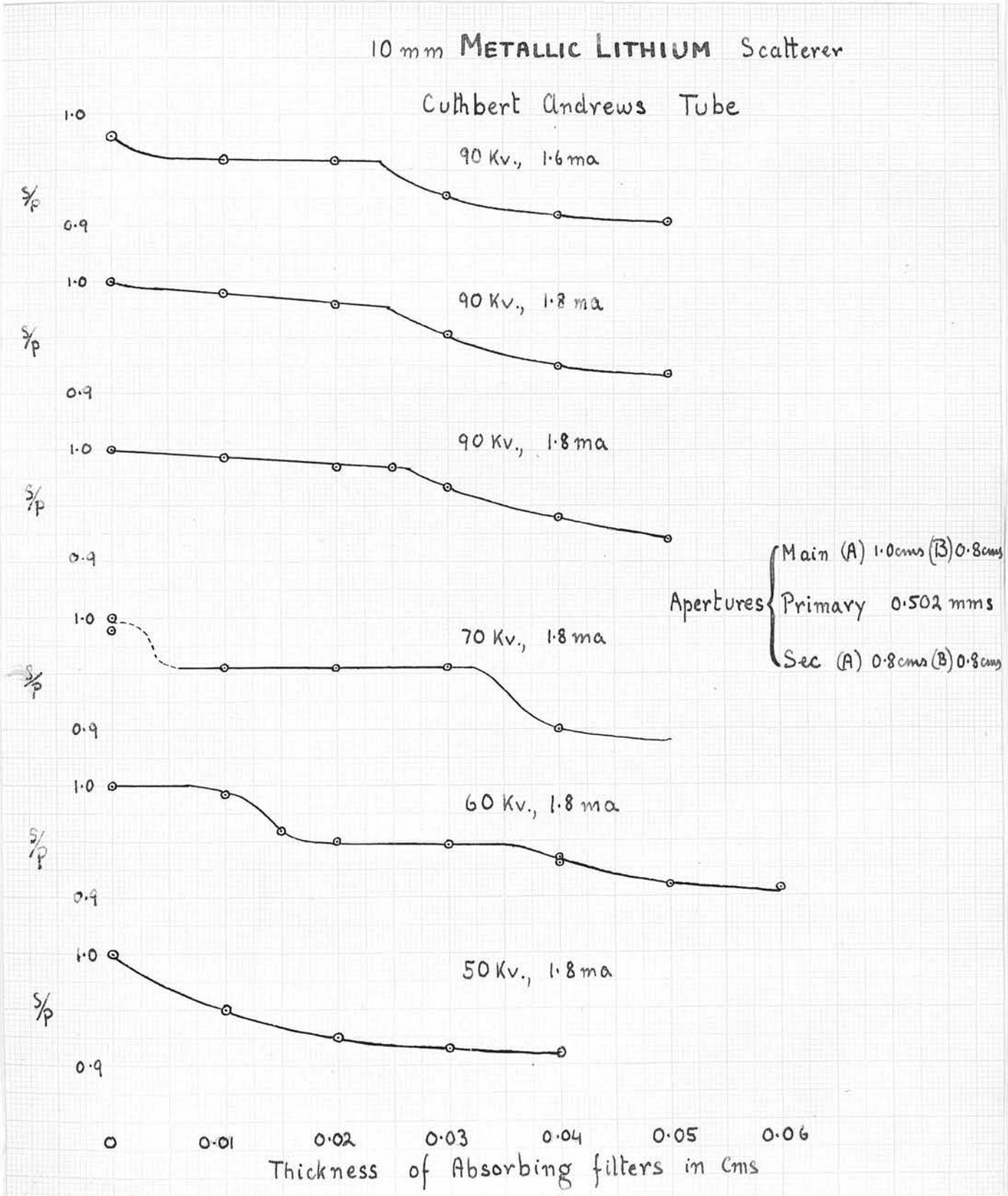


Fig 42

The results shown in Fig. 42 seem to indicate that:

(1) As the voltage across the tube is decreased, the discontinuity appears to undergo a considerable shift to the right, i.e. to larger values of the critical thicknesses of the absorbing filters, this shift being accompanied by the appearance of new discontinuities within the range of filters used.

(2) Certain critical voltages, in this case 70-60 Kv., seem to stress the abruptness of the discontinuities.

(3) Below about 60-50 Kv. no discontinuities were found in the range of filter thicknesses used.

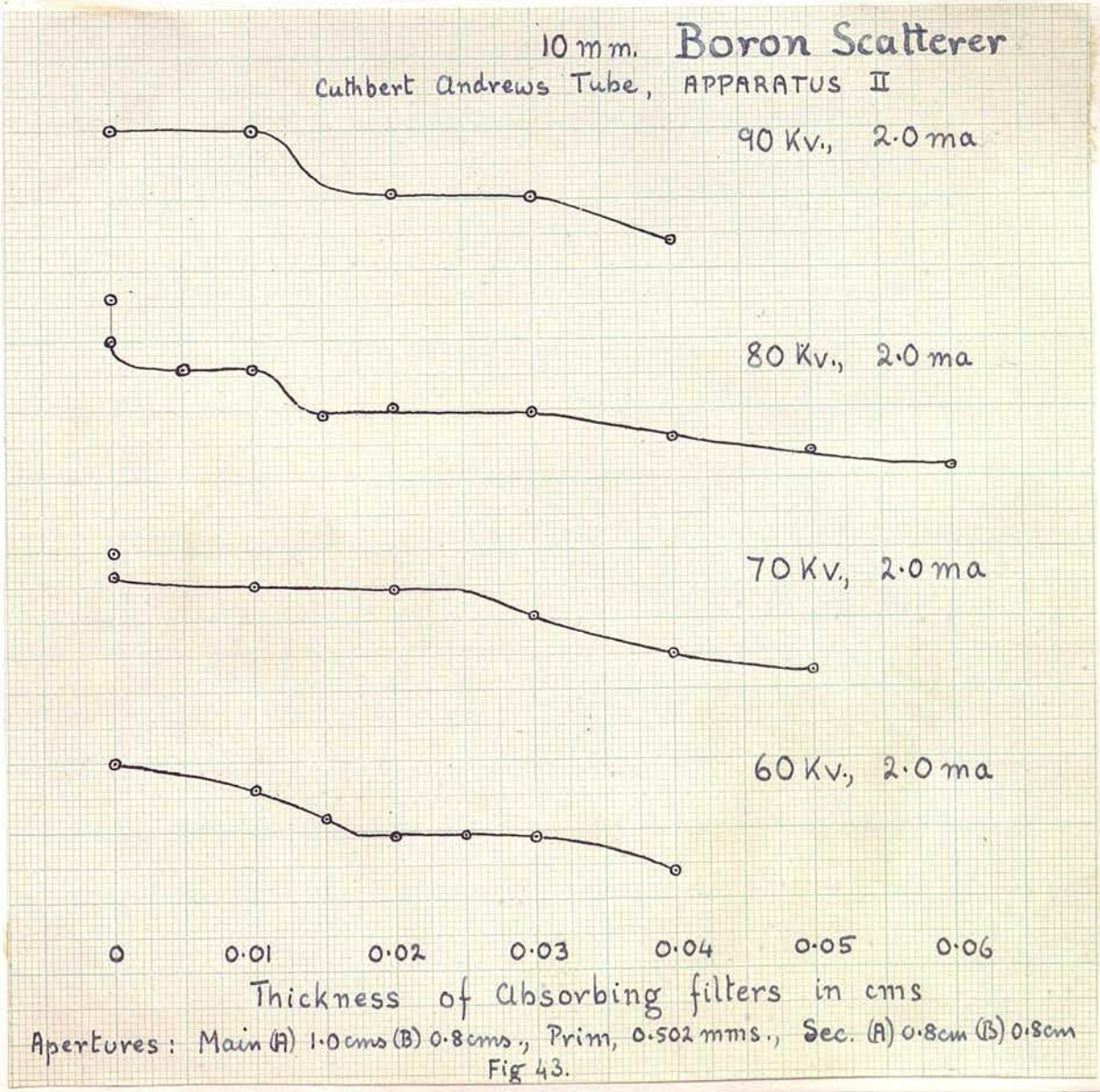


Fig 43.

The results obtained with a 10 mm. Boron scatterer, shown in Fig. 43, also seem to confirm the deductions derived from the results obtained with a 10 mm. Lithium scatterer.

It seems, therefore, that the appearance of a particular discontinuity is associated with a certain degree of hardness of the radiation used. Thus when lower potentials are used, greater thicknesses of primary and secondary filters have to be used in order to obtain the corresponding 'kink' or discontinuity.

It is, however, difficult to be absolutely certain of this deduction, as the identification of a particular discontinuity in its various positions as the potential applied to the tube is varied, is in some cases somewhat uncertain, especially so as the kinks often become blurred and 'stretched out' with a change in voltage. In fact, some previous workers appear to have differed in their opinions of the direction of the shift of the discontinuities with change of voltage across the tube. The majority of them, however, expressed the same conclusions as deduced by the present writer from his experimental results.

It is interesting to note, however, that with a Boron scatterer, the discontinuities or 'kinks' appear to be most marked when the X-ray tube is excited with a potential difference of 90 Kv., whereas with a Lithium scatterer, of the same thickness, the 'kinks' or discontinuities were most marked at a potential difference of 60 Kv.

It thus seems that as the atomic number of the scatterer is raised, the voltage required to produce marked 'kinks' also

increases.

The dependence of the appearance of a marked discontinuity on the atomic number of the scatterer is seen by comparing Figs. 42, 43 and 45, showing results obtained with Lithium, Boron, and Beryllium Oxide scatterers respectively. (The two former were obtained under identical conditions of apertures, etc., but the Beryllium Oxide, being a very poor scatterer, necessitated a slight increase in one of the secondary apertures, as indicated in Fig. 46).

The dependence of the discontinuity on the atomic number of the scatterer is also strikingly shown in Fig. 44, the upper curve of which was obtained with a 10 mm. Boron scatterer and the lower curve with a 3 mm. Paraffin Wax scatterer. This thickness of Paraffin Wax was chosen so as to give almost the same ionisation ratio $^{S}/_{P}$ and times of readings as the 10 mm. Boron scatterer, using the same apertures and tube current.)

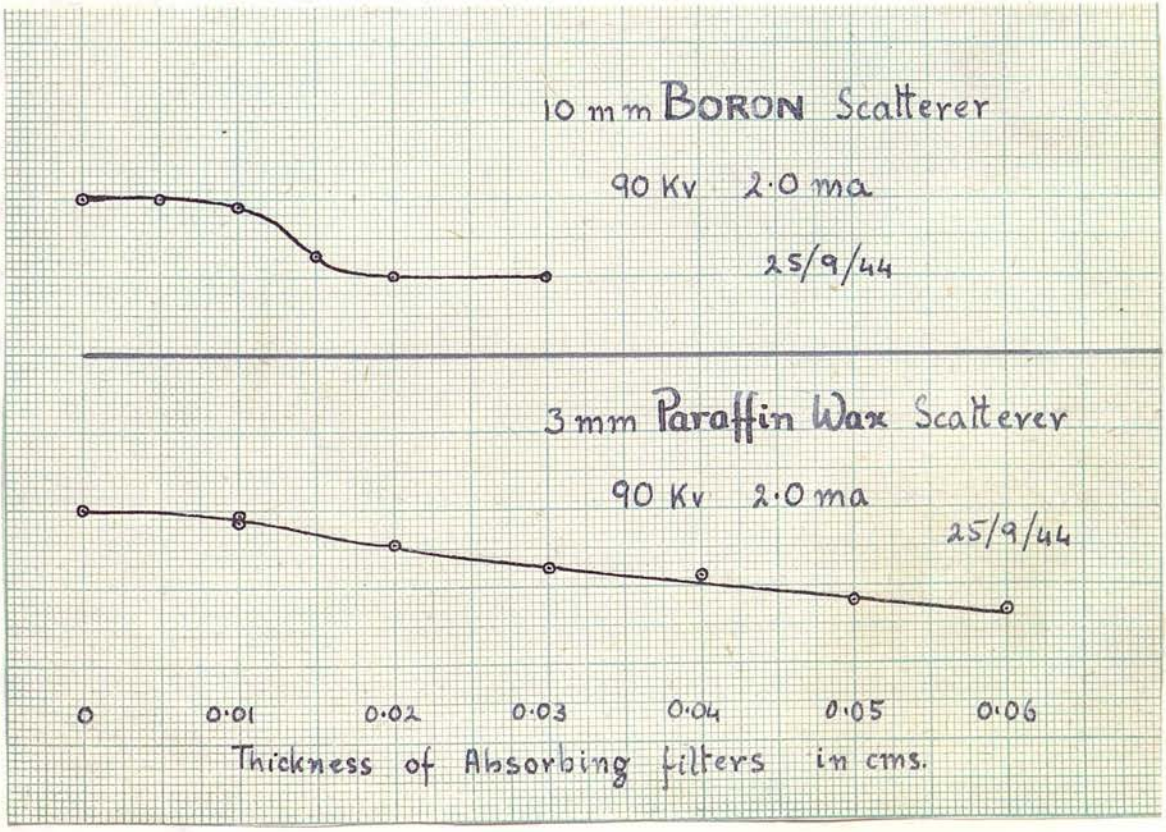


Fig 44

The two curves were obtained under identical conditions on the same day.

The Paraffin Wax scatterer shows only a trace of a 'kink' for a critical filter thickness of about 0·01 cms. of Aluminium, whereas the Boron scatterer again shows a marked 'kink' at about the same critical thickness of absorbing Aluminium.

In the light of the results obtained with Lithium, Boron, and Beryllium Oxide scatterers, it seems probable that if a high enough voltage could be applied to the X-ray tube, the Paraffin Wax scatterer might also show marked discontinuities.

The direct comparison of the 10 mm. Boron curve with the 3 mm. Paraffin Wax curve may, however, be unjustifiable owing to the difference in the thicknesses of the two scatterers, as some previous workers found that the occurrence of the discontinuities seemed to depend on the thickness of the scatterer.

In order to eliminate this possibility, and to compare the results obtained from Carbon and Boron scatterers, the filtering experiment was repeated with a 10 mm. Boron scatterer, and a 9 mm. Carbon (graphite) scatterer. (Since the Carbon scatterer was a much more effective scatterer than the Lithium or Boron scatterers, the main primary aperture was increased slightly and the two ionisation ratios in this case were very different.

The results are shown in Fig. 45. We again find a marked 'kink' with the Boron scatterer, at a critical filter thickness of about 0·01 cms. of Aluminium, but only a trace of a

'kink' at about the same critical thickness of absorbing Aluminium with the Carbon scatterer. In this case, however, the thicknesses of the two scatterers, 10 mm. and 9 mm. respectively are comparable, and so presumably do not affect the results.

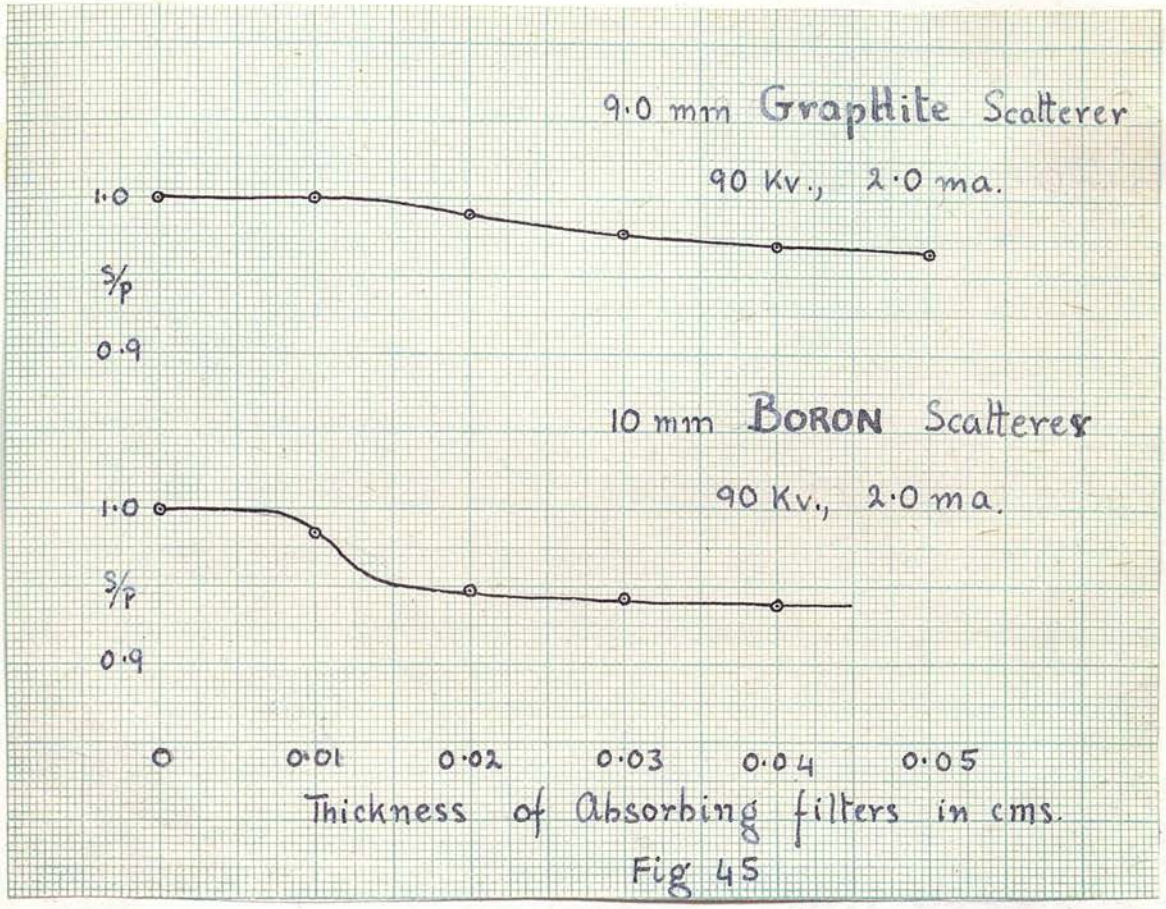


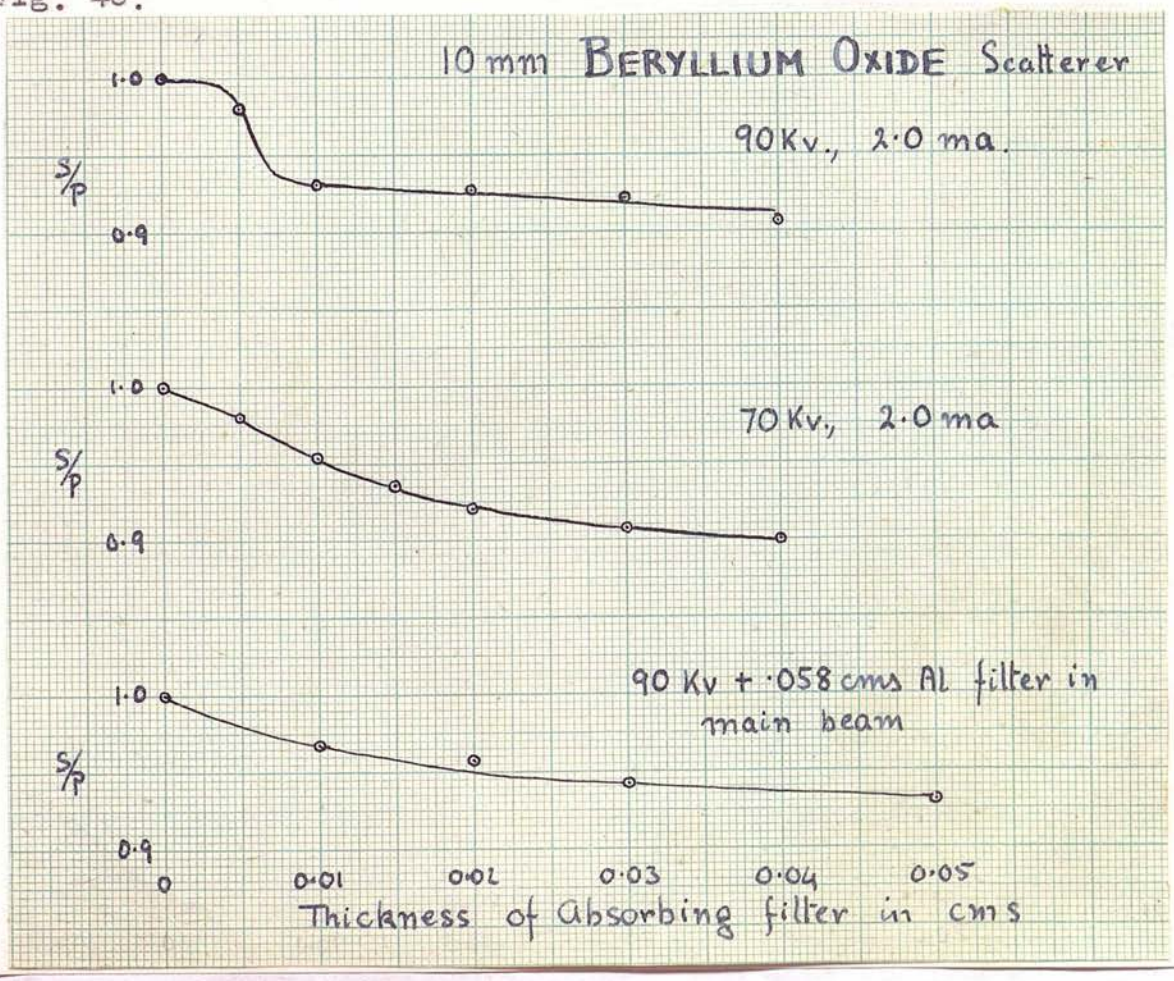
Fig 45

Thus between the results shown in Figs. 44 and 45, it seems reasonable to conclude that with a voltage of 90 Kv. across the X-ray tube and a tube current of 2·0 ma. The Boron (Atomic No.5) scatterer systematically showed marked kinks at a critical filter thickness of about 0·01 cms. of Aluminium, while Paraffin Wax (a mixture of Hydro Carbons) and Carbon (Atomic No.6) only showed relatively slight traces of 'kinks' at about the same critical thickness of absorbing Aluminium.

In other words, the discontinuities seem to be much more marked for scatterers of low atomic number, and in particular, for the voltage range used in the above experiments (up to a maximum of 90 Kv.) marked discontinuities were only observed with Lithium, Beryllium Oxide, and Boron scatterers, the atomic numbers of both of which are less than 6, the atomic number of carbon.

Thus in our experiments with the Cuthbert Andrews tube it seemed that marked discontinuities were observed only with scatterers having atomic numbers less than 6.

In order to check this conclusion, it was very desirable to use a Beryllium scatterer. Unfortunately, however, every attempt to obtain metallic Beryllium in the form of a slab or fine powder was unsuccessful and we were obliged to use a finely powdered Beryllium Oxide scatterer. The results obtained with a 10 mm. B_eO scatterer are shown in Fig. 46.



Here again we find a very marked 'kink' or discontinuity when the voltage across the tube was 90 Kv. This 'kink' was quite stable and the various readings could be repeated at will. When, however, attempts were made to investigate the effect of lowering the voltage the 'kink' practically disappeared, as shown in the 70 Kv. curve in Fig. 46.

The effect of hardening the incident radiation by filtering through Aluminium sheets placed between the scatterer and the X-ray tube was then tried. Here again no 'kink' was found, as shown in the lowest curve of Fig. 46.

These results seem to indicate that the appearance of a marked 'kink' is dependent on the 'degree of hardness' of the incident radiation, produced by a certain potential difference applied to the X-ray tube, and that any change in the 'degree of hardness' of the incident radiation produced by altering the voltage across the X-ray tube, or by filtering the incident radiation is associated, in the case of a Beryllium Oxide scatterer, with the disappearance of the 'kink'.

THE SCATTERING EXPERIMENT.

In this type of experiment, the ratio of the ionisations produced by the transmitted and scattered beams are compared for different 'degrees of hardness' of the radiation incident on the scatterer. The 'degree of hardness' of the incident radiation was varied by:

(1) Altering the potential difference across the tube.

or (2) Inserting various thicknesses of Aluminium filters between the X-ray tube and the scatterer.

The 'degree of hardness' of the radiation was measured in terms of the mass absorption coefficient of the primary beam in Aluminium, measured by the conventional 50% reduction of intensity already described.

The ionisation ratios $^{S}/_{P}$ were then plotted against the corresponding mass absorption coefficients.

A typical result of such an experiment is shown in Fig. 50.

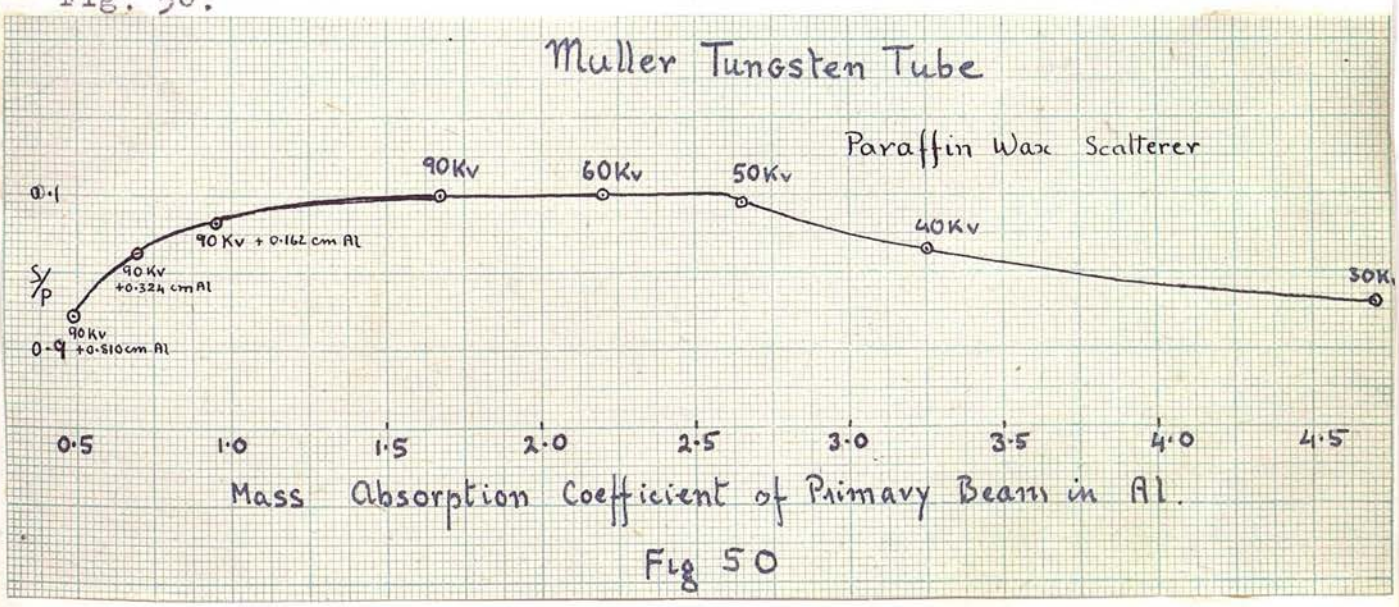


Fig 50

and illustrates the following points.

(1) As the potential difference across the tube is raised from 30 Kv. to 45 Kv. the ionisation

ratio $^{S}/_{P}$ steadily increases.

(2) For a further increase in the potential difference across the tube, up to 90 Kv. (the maximum working voltage used) the ionisation ratio is remarkably constant.

(3) If the hardness of the incident radiation is increased by inserting filtering sheets of Aluminium between the X-ray tube and the scatterer, the ionisation ratio $^{S}/_{P}$ decreases as thicker filters are used.

The result described above was obtained almost invariably. In fact, several hundreds of these curves under various experimental conditions were obtained by the writer. These curves were nearly all of much the same shape but the critical potential at which the curve flattened out seemed to vary with some experimental parameters. The dependence of this critical potential, and of the rate of decrease of the ionisation ratio $^{S}/_{P}$ as thicker filters are interposed between the scatterer and the tube on the various experimental parameters were carefully investigated and the results shown below.

(1) Scattering Experiments with Different X-ray Tubes.

When the experiments were performed with different types and makes of tubes, the results showed that the critical voltage across the tube, below which a decrease in the voltage was associated with a decrease in the ionisation ratio $^{S}/_{P}$, depended on the particular X-ray tube used.

Curves (a), (b) and (c) of Fig. 51 show the typical

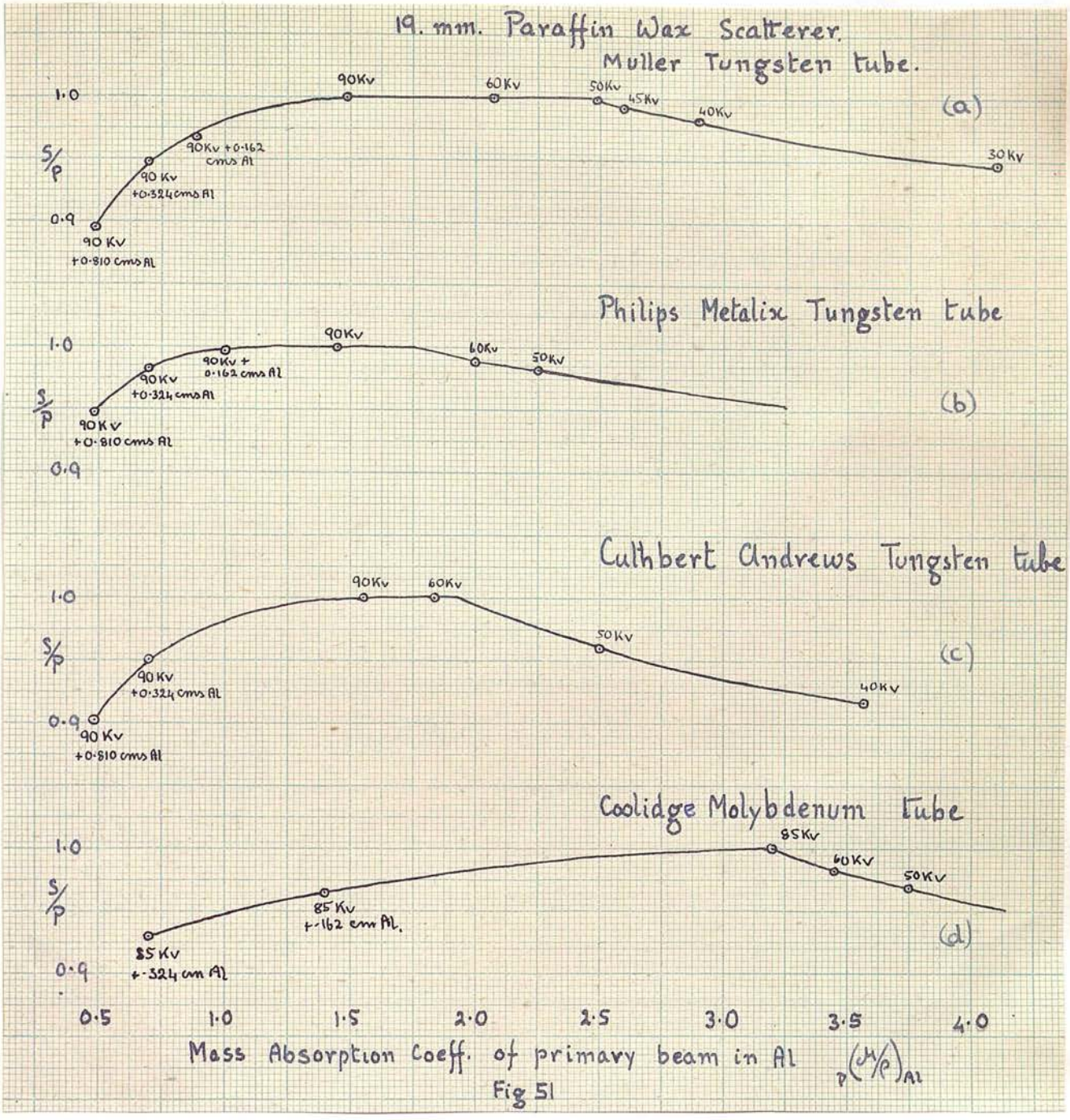


Fig 51

results obtained by using Muller, Philips Metalix, and Cuthbert Andrews hot cathode Tungsten target tubes respectively, under similar experimental conditions, the details of which are given in the figure.

These results all show that over a certain voltage range the ionisation ratio S/p remains horizontal up to a certain critical voltage, below which the ionisation ratio decreases as the voltage across the tube is decreased.

Also all three curves show that if a potential difference

of 90 kilo-volts is maintained across the tube and aluminium filters are inserted between the tube and the scatterer thereby hardening the incident radiation, the ionisation ratio decreases as thicker filters are used. The rate of decrease in the ionisation ratio is also seen to depend on the particular tube used.

The decrease in the ionisation ratio S/P with the Muller tube operated at a potential difference of 90 Kv. and the radiation filtered through 0·810 cms. of Aluminium was of the order of 10 per cent, whereas for the Philips Metalix tube under similar conditions, the corresponding difference in the ionisation ratio for the unfiltered and filtered radiations was only of the order of 5 per cent of the unfiltered ratio, although the mass absorption coefficients of the radiations emitted by both these tubes under given conditions were very similar.

Curve (d) in Fig. 51 was obtained with a hot cathode Molybdenum Target tube. This tube showed a marked difference when compared with the Tungsten target tubes in that there did not seem to be any voltage range over which the ionisation ratio was constant.

The maximum voltage which could be applied to this tube was 85 Kv. and as soon as the voltage was lowered, the ionisation ratio S/P was found to decrease. The radiations emitted by this tube for a given potential difference across it were much 'softer' or more absorbable than the corresponding radiations from the Tungsten target tubes.

It was therefore thought that hardening the radiations by

filtering between the tube and the scatterer might show a range of mass absorption coefficients over which the ionisation ratio would be constant, but experiment showed no sign of any horizontal portion of the curve corresponding to a constant ionisation ratio for different mass absorption coefficients. In fact, the insertion of a filter of Aluminium between the tube and the scatterer produced a marked decrease in the ionisation ratio. The decrease in the ratio for a given thickness of Aluminium filter was greater with the Molybdenum target tube than with a Tungsten target tube.

With a filter of 0·324 cms. of Aluminium the ionisation ratio dropped by 7 per cent in the case of the Molybdenum tube, but only by 5 and 2 per cent for the Muller and Philips Tungsten tubes respectively.

The cause of the difference in the type of result obtained with the Molybdenum tube as compared with the Tungsten tubes appears to lie principally in the difference of the elements composing the targets of the tubes, although there is a considerable amount of uncertainty in such a conclusion owing to the considerable differences in the structure of the Molybdenum tube as compared with the Tungsten tubes. The most marked difference is that the Molybdenum tube is supposed to be 'Helium Filled' and has its target inclined at an angle of almost 88° to the axis of the tube; the actual target of this tube is slightly convex. The Tungsten tubes, on the other hand, were all 'hard vacuum pumped' tubes, with their targets inclined at an angle of about 71° to the axis of the tube.

The scattering experiments were also tried with the Molybdenum tube set so that its axis was inclined at an angle of about 45° to the axis of the apparatus. No marked difference in the shape of the resulting curve was found, and thereby seemed to indicate that the angle of the Molybdenum target and its convexity were not the cause of the marked difference of the results obtained with the Molybdenum and Tungsten tubes.

(2) Scattering Experiments with Scatterers of Different Thicknesses.

The effect of the thickness of the scatterer used was investigated by making several scatterers of Paraffin Wax ranging from 1·9 to 0·3 cms. in thickness. (Paraffin Wax was used owing to its abundance and ease of manipulation). The results obtained with a Muller Tungsten tube for Paraffin Wax scatterers 1·9, 1·1 and 0·3 cms. thick are shown in Fig. 52.

The most marked feature of these results is the considerable extension of the range of mass absorption coefficients over which the ionisation ratio S/P remains constant with change in voltage across the X-ray tube, as the thickness of the scatterer is decreased.

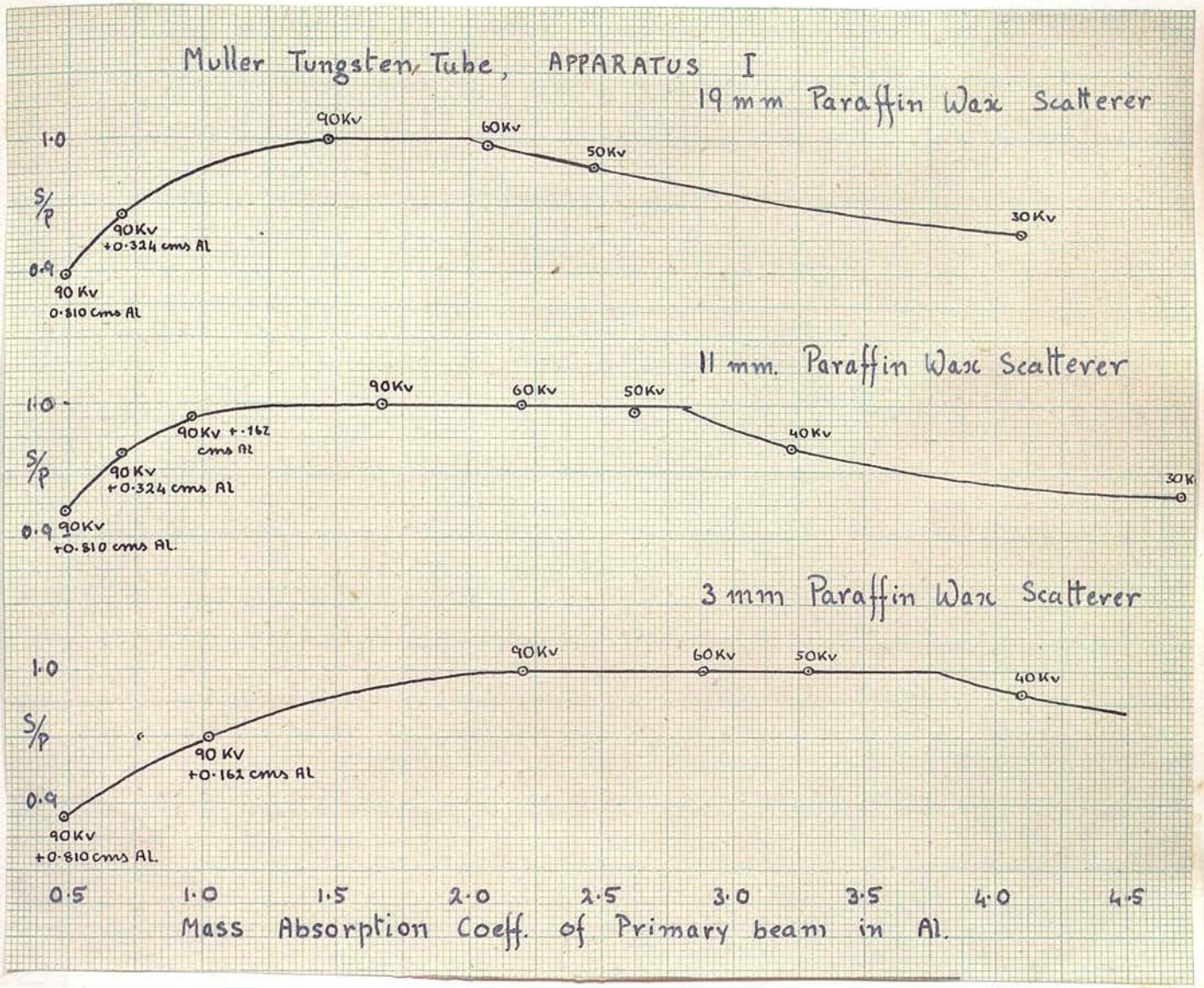


Fig. 52.

This striking effect produced by simply changing the thickness of the scatterer has been confirmed by experiments with the Philips Metalix and Cuthbert Andrews Tungsten tubes, Fig. 53. (Unfortunately the Molybdenum tube was unavailable to the writer for this type of experiment.)

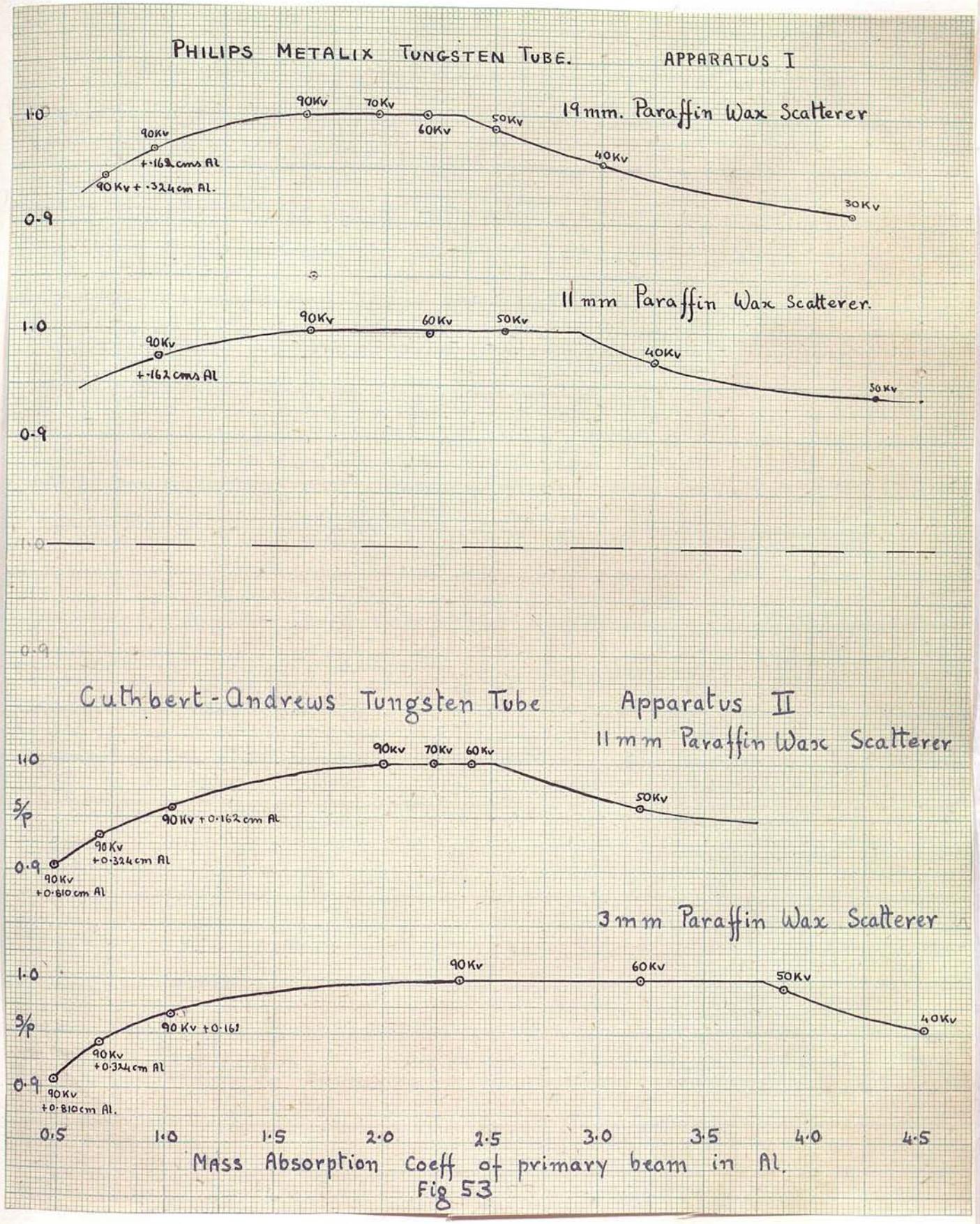


Fig 53

The effect has also been well established by other workers in this laboratory.

A discussion of the possible causes of the abrupt change of the scattering curves from horizontality and the dependence of the critical voltage across the X-ray tube producing this change on the thickness of the scatterer will be given later under the heading of 'Discussion of results'.

In the meantime, it is sufficient to indicate that the effect was found with two different sets of apparatus, involving radically different arrangements and dimensions of apertures, as shown in Fig. 53 for apparatus I and apparatus II. This fact, taken in conjunction with the results obtained under various conditions by other workers, seems to establish the effect as a genuine one and not as an effect arising from any faulty arrangement of the apparatus or observational error.

(3) Scattering Experiments with Scatterers of Different Atomic Number.

For convenience, the scatterers used were mainly 1·0 cms thick, although the Paraffin Wax scatterer was 1·1 cms and the Carbon scatterer 0·9 cms. in thickness.

Unfortunately, in order to get comparable values of the ratios $^{S}/_{P}$ some of the scatterers necessitated the use of slightly different apertures but auxiliary experiments have shown that the actual changes made in apertures in these particular experiments did not affect the results. (This will be considered in detail below.)

The results obtained with Metallic Lithium, Amorphous Boron, Beryllium Oxide, Paraffin Wax and Carbon (graphite) scatterers 1·0 cms. in thickness are shown in Fig. 54.

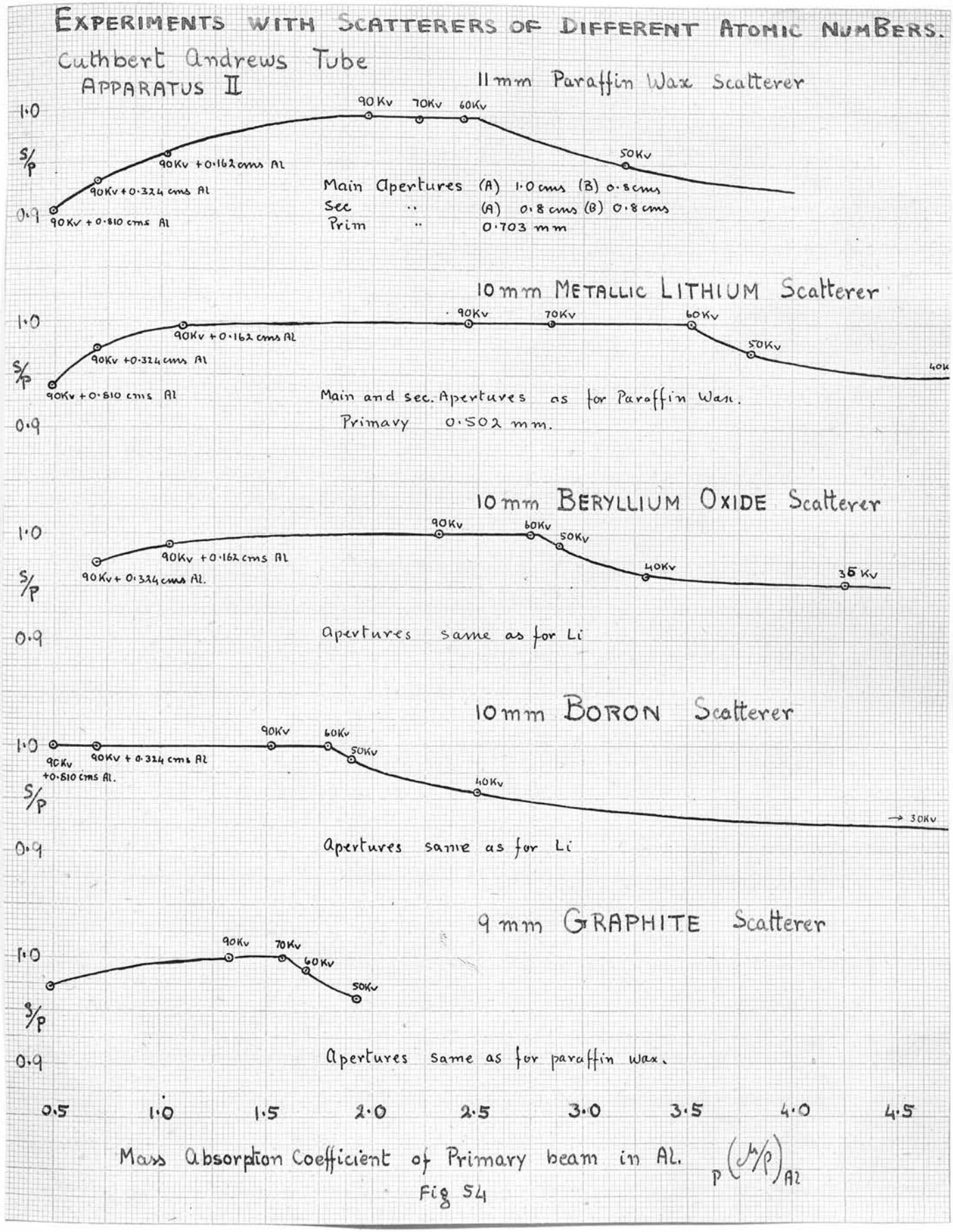


Fig 54

These results were obtained under some of the best working conditions, with a new Cuthbert Andrews Tungsten tube and

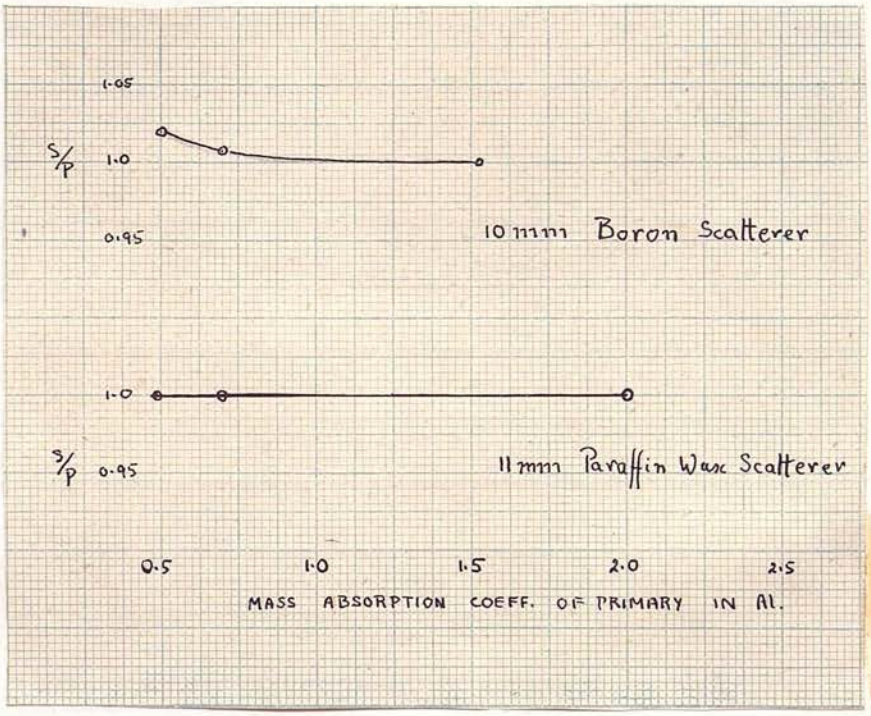

1.05
S/P 1.0
0.95
10 mm Boron Scatterer
1.0
S/P 0.95
11 mm Paraffin Wax Scatterer
0.5
1.0
1.5
2.0
2.5
MASS ABSORPTION COEFF. OF PRIMARY IN Al.

Fig 54'

are considered by the writer as being particularly reliable.

With the exception of Boron, all these scatterers gave curves very similar to the ones obtained with the Paraffin Wax scatterers as already described.

As can be seen from Fig. 54, there seems to be some indication of not only a bigger range of mass absorption coefficients over which the ionisation ratio remains constant as the atomic number of the scatterer decreases, but also of a slightly bigger range of voltages applied to the X-ray tube, over which the ionisation ratio is constant.

Among all the scatterers used by the writer, Boron was unique in giving a constant value of the ionisation ratio S/p for all thicknesses of Aluminium filters up to 0·810 cms inserted between the scatterer and the tube, the latter running at 90 Kv. This result had been checked and re-checked under various conditions and the distinct difference of a Boron scatterer compared to a Paraffin scatterer in this respect seems to have been established beyond doubt.

In particular, under certain conditions (to be described below) a 11 cm. Paraffin Wax scatterer was found to give a constant ionisation ratio when filters up to 0·810 cms. of Aluminium were placed between the X-ray tube and the scatterer. Under these conditions, the Boron scatterer produced an increase in the ionisation ratio S/p as thicker Aluminium filters were inserted between the tube and the scatterer, as shown in Fig. 54.

When, however, normal conditions were returned to and a decrease of the ionisation ratio S/P was observed with a

1·1 cm. Paraffin Wax scatterer, the Boron scatterer was found to give a constant ratio for all thicknesses of Aluminium filters from 0 to 0·810 cms. (the maximum thickness used). In both cases the times required for the various readings were nearly the same. In fact, the only difference between the Paraffin Wax and Boron experiments, the results of which are shown in Fig. 54, is that primary apertures of 0·50 mm. and 0·705 mm. in diameter were used with the Boron and Paraffin Wax scatterers respectively.

Separate experiments, described below, show that the difference in the result obtained with Paraffin Wax and Boron scatterers are not likely to be due to the difference in primary apertures used in these cases.

Another interesting feature illustrated in the curves shown in Fig. 54 is that in general, Lithium and Beryllium Oxide scatterers show a much smaller decrease in the ionisation ratio S/P for a given thickness of filtering Aluminium inserted between the tube and the scatterer, than the corresponding drop in the ionisation ratio when a Paraffin Wax scatterer is used. Thus, for example, the introduction of 0·324 cms. of Aluminium between the tube and a 1·1 cm. Paraffin Wax scatterer produced a drop of 10 per cent in the ionisation ratio; the corresponding drops with Lithium, Beryllium Oxide, Boron and Carbon scatterers were 7, 5, 0, 5 per cent respectively.

The results shown in Fig. 54 seem to show that as the atomic number of the scatterer decreases below that of Boron, atomic number 5, the decrease of the ionisation ratio S/P as thicker filters are inserted between the tube and the

scatterer increases.

From this point of view, the relatively large decrease in the ionisation ratio obtained with a Paraffin Wax scatterer may be attributed to the scattering from Hydrogen in the Paraffin Wax.

It follows also that we might reasonably expect scatterers of atomic numbers higher than Boron to give either a constant or increasing ratio as thicker filters are used. Experiments with Carbon (compressed graphite blocks) however show that the ionisation ratio S/P again decreases as thicker filters are placed between the tube and the scatterer. This unexpected result may be due to some impurity containing hydrogen or other light element used as a binder in the graphite block, or, and more probably, it may be an intrinsic property of the carbon atoms themselves.

The latter conclusion obtains some confirmation from the fact that some test experiments made with pure Aluminium scatterers also showed a marked decrease in the ionisation ratio S/P as shown in Fig. 55, when Aluminium filters were inserted between the tube and the scatterer.

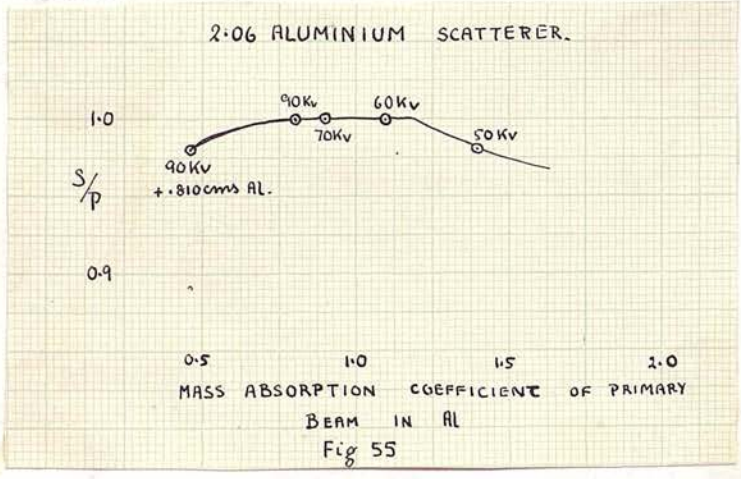


Fig 55

Scatterers of low atomic number thus seem to produce a much smaller rate of decrease of the ionisation ratio S/P

with increasing thickness of filtering Aluminium than was obtained with Paraffin Wax scatterers.

(4) Scattering Experiments with Scatterers in Solid and Liquid States.

These experiments were only attempted with Paraffin Wax owing to the low melting point of this material. The technical details of the scatterer have been given on page 47 and a direct comparison of the results obtained with solid and liquid Paraffin Wax scatterers of the same thickness and under the same conditions is shown in Fig. 56.

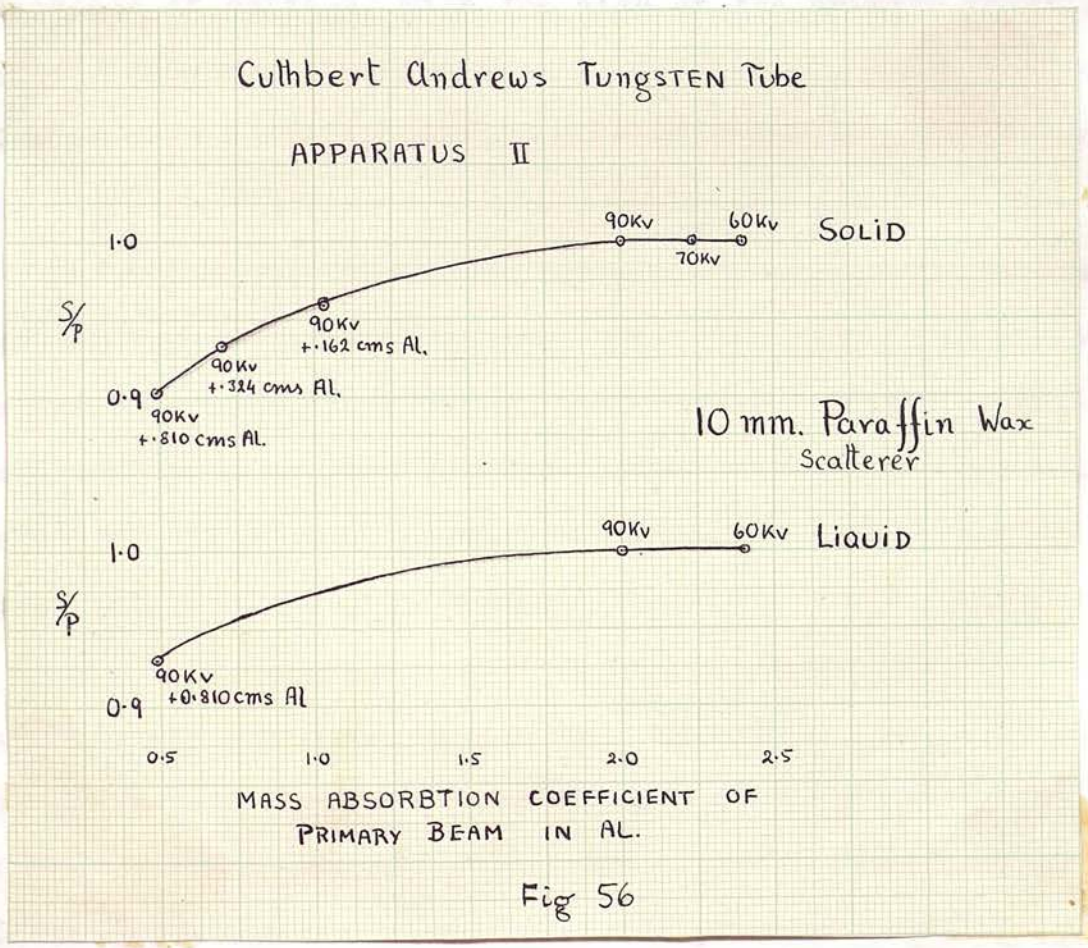


Fig 56

These results show that the decrease of the ratio S/p with the insertion of Aluminium filters between the scatterer and the tube is of the same order of magnitude for solid and liquid scatterers.

Unfortunately the life of a liquid scatterer of the type used was only about three hours, as at the temperature of the liquid wax the cellophane windows invariably dehydrated, became brittle and burst, so that a lengthy experiment could not be carried out with them.

(5) Scattering Experiments with Various Primary Apertures.

Some workers in this laboratory claim to have found a definite variation of the critical potential across the X-ray tube (below which the ionisation ratio decreases with decrease of voltage) with the size of the primary aperture used. They seem to find that the voltage range over which the ionisation ratio S/P remains constant is extended towards the low voltage side by using smaller primary apertures.

The writer has carried out a large number of experiments with a wide variety of primary apertures ranging from single holes to groups of very find holes and also with adjustable slits consisting of 4 mm. lead jaws. Some of the typical results obtained are shown in Fig. 57, together with the details of the apertures etc.

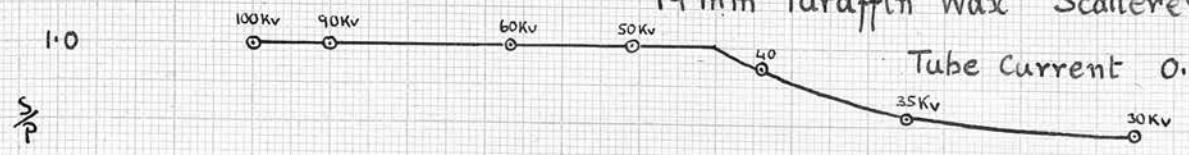
These experiments were carried out with great care and appropriate corrections made for the natural leaks as already described. A single curve sometimes took between 3 to 6 hours for completion and for this reason, it was decided to investigate the effect of different primary apertures on the critical voltage, and on the decrease of the ionisation ratio S/p with increase of thickness of filtering Aluminium inserted between the X-ray tube and the scatterer separately.

EXPERIMENTS WITH DIFFERENT APERTURES

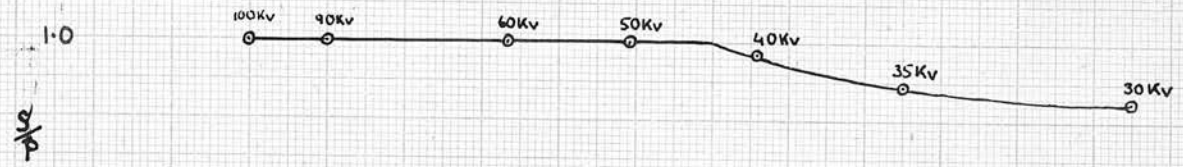
MULLER TUNGSTEN TUBE

19 mm Paraffin Wax Scatterer.

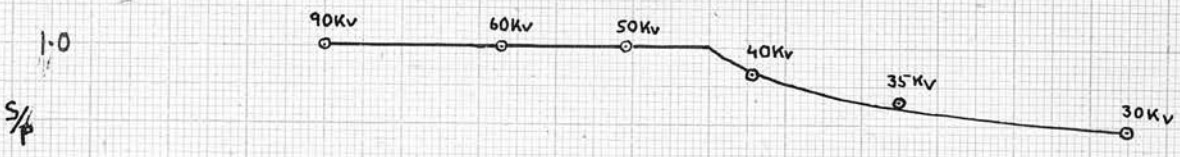
Tube Current 0.6 ma



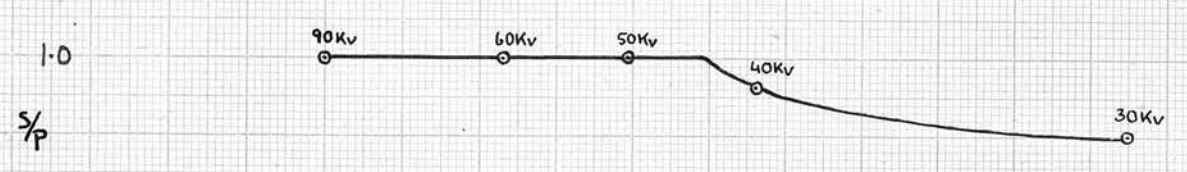
Primary aperture : 39 pinholes, 0·41 mms in diam.
Secondary (A) 2·2 cms B 2·2 cms.



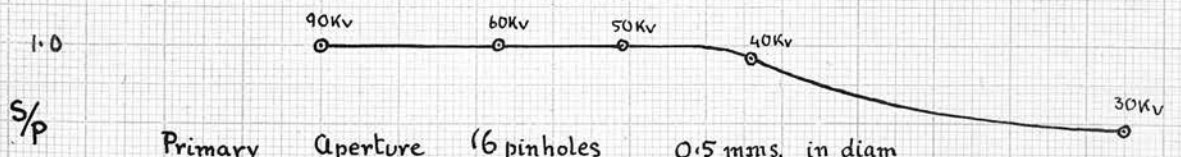
Primary Aperture : Single hole 2·5 mms in diam
Secondary Aperture (A) 2·2 cms (B) 2·2 cms.



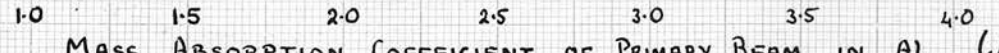
Primary Aperture : 25 pinholes 0·5 mms in diam
Secondary Aperture (A) 2·2 cms (B) 2·2 cms



Primary Aperture 25 pinholes 0·5 mms in diam
Secondary Aperture (A) 1·3 cms (B) 2·0 cms



Primary Aperture 16 pinholes 0·5 mms. in diam
Secondary Aperture (A) 1·0 cms (B) 1·3 cms.



MASS ABSORPTION COEFFICIENT OF PRIMARY BEAM IN AL. $\left(\mu/\rho\right)_{Al}^{P}$

Fig 57.

The results shown in Fig. 57 are those where the dependence of the critical voltage alone on the primary aperture was investigated; while the results shown in Fig. 59 show the effect of the primary aperture (a variable slit) on the decrease of the ionisation ratio with increasing thicknesses of Aluminium filters between the tube and the scatterer.

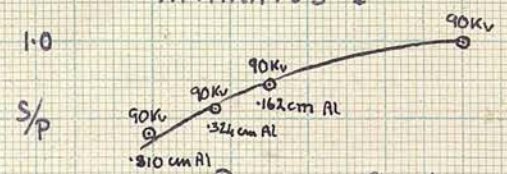
It will be seen from the curves shown in Fig. 57 that the critical voltage, below which the ionisation ratio S/p is no longer constant but begins to decrease, appears to be independent of the primary aperture ranging from a single hole 2·5 mm. in diameter to 39 pin holes having a diameter of 0·41 mms. each.

The critical voltage also appears to be practically independent of the secondary apertures when the latter are varied between 2·2 and 1·0 cms. for aperture A and between 2·2 and 1·3 cms. for aperture B.

With the Muller Tungsten tube and scattering from a Paraffin Wax scatterer 1·9 cms. in thickness, the critical voltage was found to be practically independent of the primary and secondary apertures within the stated ranges and was found to have a value of 43 to 45 kilo volts.

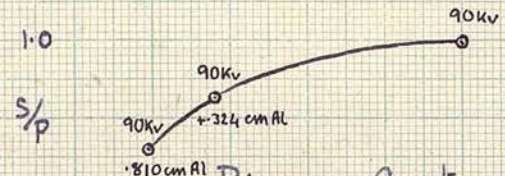
MULLER TUNGSTEN TUBE

APPARATUS I



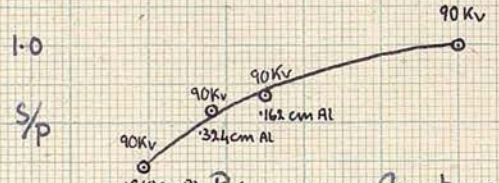
19 mm Paraffin Wax Scatterer

Primary Aperture Single hole 2·5 mm in diam
Secondary Aperture (A) 2·2 cms (B) 2·2 cms



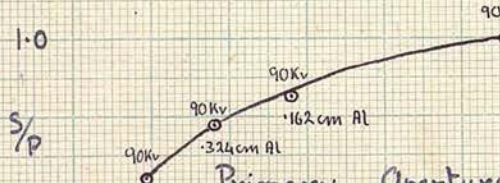
19 mm Paraffin Wax Scatterer

Primary Aperture 25 pinholes 0·5 mm in diam
Secondary Aperture (A) 2·2 cms (B) 2·2 cms



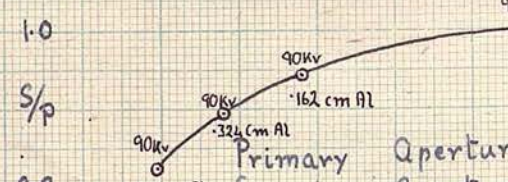
19 mm Paraffin Wax Scatterer

Primary Aperture: 25 pinholes 0·5 mm in diam
Secondary Aperture; (A) 1·6 cms; (B) 2·2 cms



11 mm Paraffin Wax Scatterer

Primary Aperture: 25 pinholes 0·5 mm in diam
Secondary Aperture: (A) 2·2 cms; (B) 2·7 cms



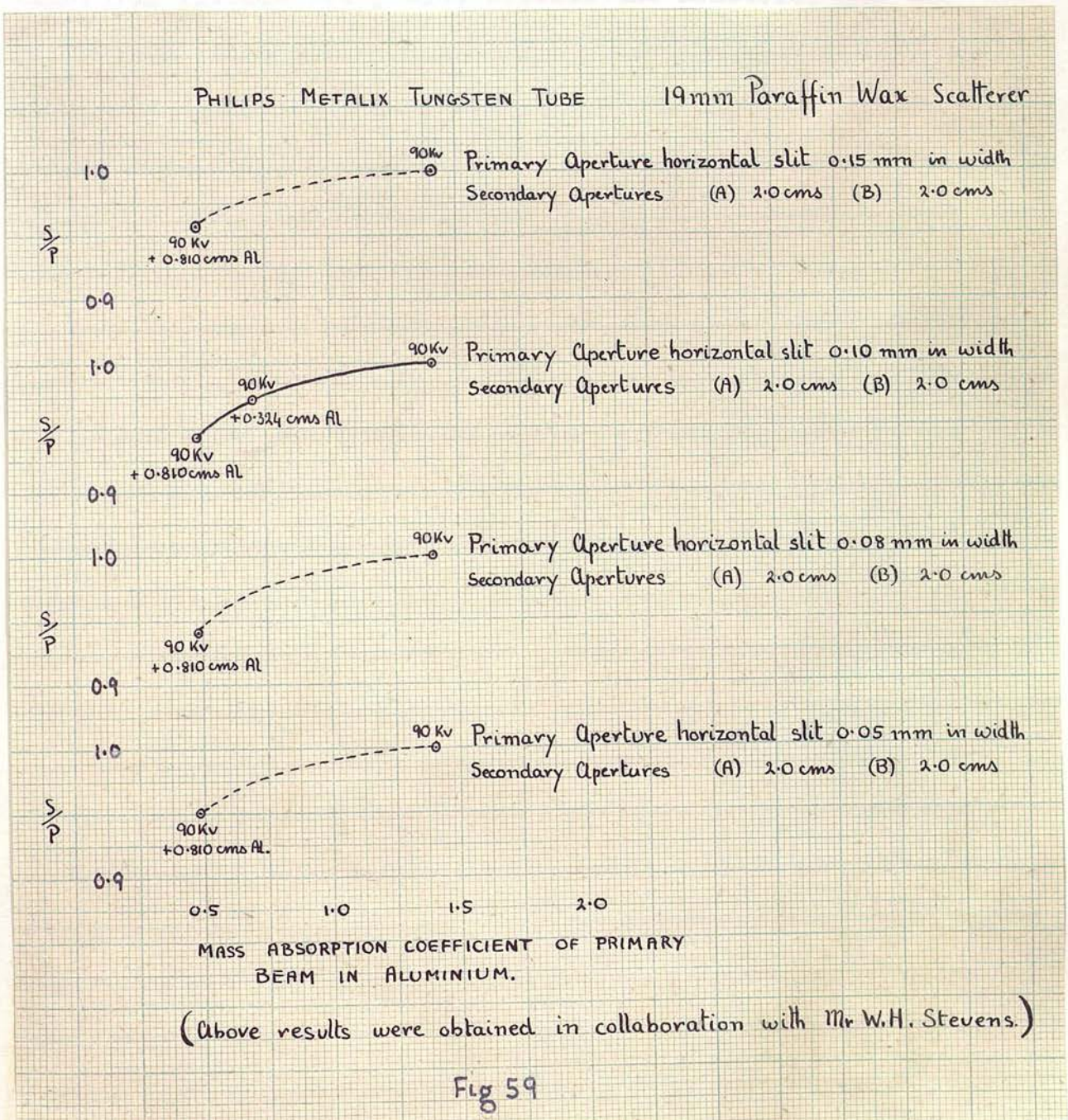
11 mm Paraffin Wax Scatterer

Primary Aperture: 6 pinholes 0·5 mm in diam
Secondary Aperture: (A) 2·2 cms; (B) 2·7 cms
Main Primary 1·0 cms

0·5 1·0 1·5 2·0 2·5
MASS ABSORPTION COEFFICIENT OF PRIMARY BEAM IN Al.

Fig 58

The effect of using various primary and secondary apertures on the decrease of the ionisation ratio when Aluminium filters are inserted between the tube and the scatterer is shown in Fig. 58; from which it will be seen that for the range of apertures used, ranging from a single hole having a diameter of 2·5 mm. to a group of 25 pin holes having a diameter of 0·5 mm, the decrease in the ratio is independent of the apertures.



(Above results were obtained in collaboration with Mr W.H. Stevens.)

Fig 59

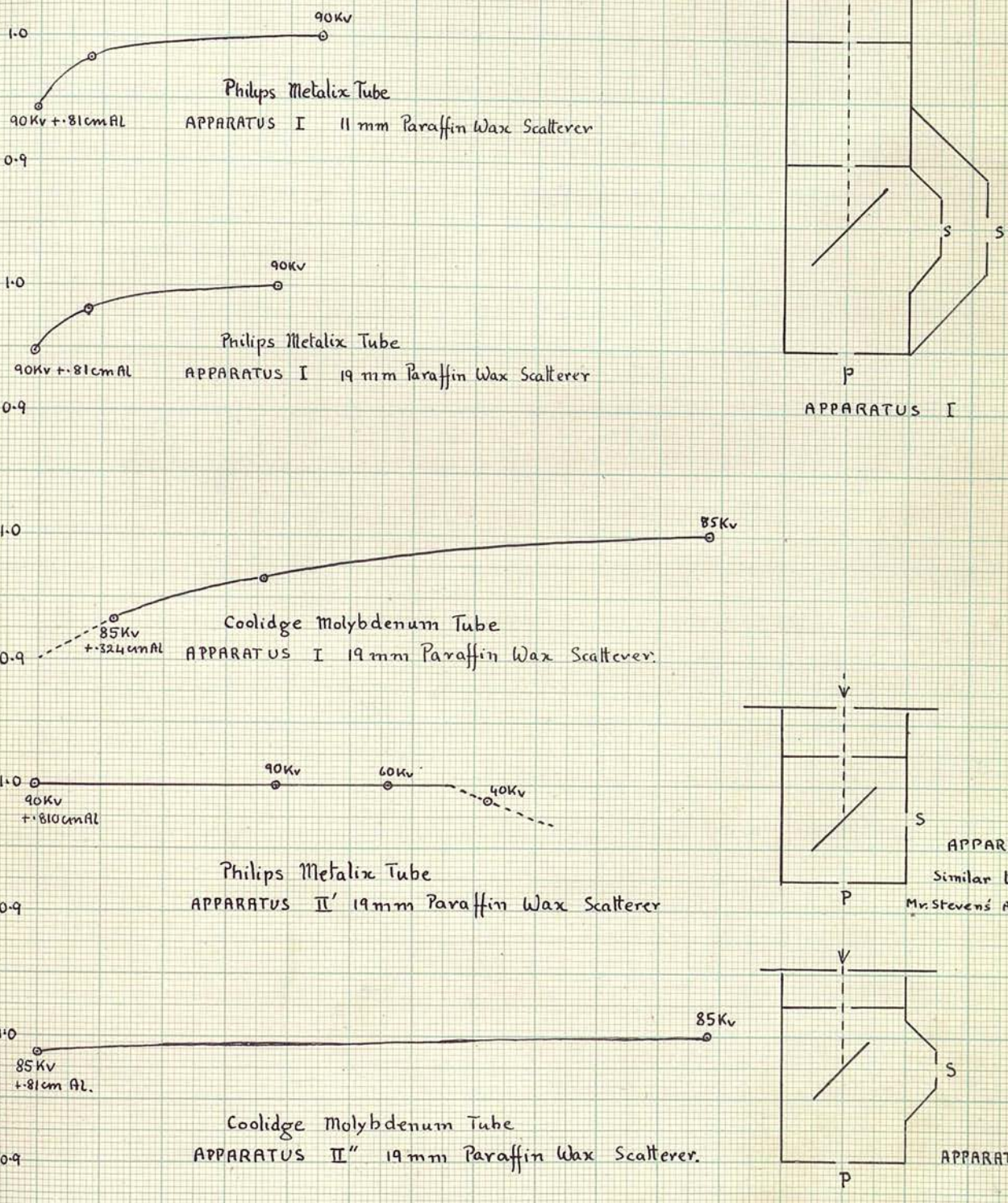
(6) Scattering Experiments with Different Arrangements of Apertures (Different Sets of Apparatus).

One of the most striking features about the scattering experiment is that although some workers find that the ionisation ratio decreases as soon as a filter of Aluminium is inserted between the tube and the scatterer, others, working in another laboratory in the same building, find that the ionisation ratio remains constant even when very thick Aluminium filters are placed between the scatterer and the X-ray tube. The ionisation ratio, in this case, appears to be independent of the hardness of the incident radiation as long as the hardness is varied by inserting different thicknesses of Aluminium filters between the tube and the scatterer, but the results obtained by altering the hardness of the incident radiation by varying the potential difference across the tube were very similar in the two cases.

It should be emphasised, however, that the workers who find a constant ionisation ratio when aluminium filters are interposed in the incident beam do find a decrease in the ionisation ratio when using thin scatterers, the drop in the ionisation ratio being more marked the thinner the scatterer.

As already described, the writer is among those who find that the ionisation ratio decreases with the insertion of Aluminium filters in the incident beam (with the exception of Boron scatterers, where the ionisation ratio was found to remain constant for all thicknesses of filters used up to a maximum of 0·810 cms. of Aluminium). The writer further found that the decrease in the ionisation ratio seemed to be independent of the thickness of the scatterer, but did depend

Mr. Stevens and the writer; these readings were always in agreement to within about one per cent.



(Above results were obtained in collaboration with Mr. Stevens)

Fig 60

The results of these experiments seem to show quite conclusively that the type of result obtained depended on the structure of the apparatus, i.e. on the positions and arrangements of the apertures and the linear dimensions of the box containing the scatterer.

It thus became possible, by using the appropriate arrangement of the apparatus, to produce at will a result showing either a constant or decreasing ionisation ratio as the thickness of the Aluminium filter between the X-ray tube and the scatterer was increased.

The type of result (a constant, or decreasing ionisation ratio) was thus dependent on the arrangement of the apparatus and not on the actual room or laboratory in which the experiment was performed - as was suggested by some previous workers in this laboratory.

The dependence of the result obtained on the arrangement of the apparatus thus raises the question as to which, if either, truly represents the scattering of radiation of different hardness by matter. This question can only be answered by careful analysis of

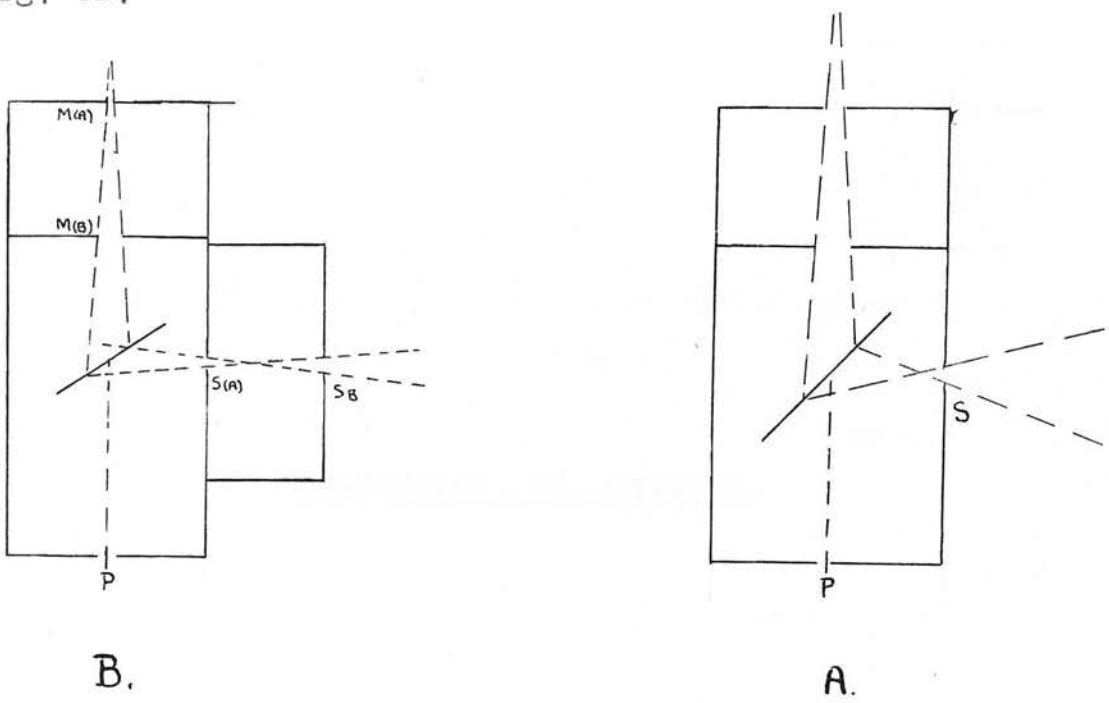
(1) The experimental parameters which seem to influence the type of result obtained,

(2) The possible ways in which these parameters can influence the result, and

(3) By carrying out test experiments in order to check the deductions made and to find which of these ways is actually responsible for the difference.

This process has been carried out and is described in the next section under the heading of 'Discussion of the

Results'. It is sufficient for the time being to draw attention to the fact that the sets of apparatus producing a constant ionisation ratio when filters of Aluminium are inserted between the tube and the scatterer differ most conspicuously from those showing a decreasing ionisation ratio by the fact that the former generally have only one effective aperture defining the scattered beam, whereas the latter generally have two such apertures as shown in A and B of Fig. 61.



B. A.

Fig. 61.

DISCUSSION OF RESULTS.

DISCUSSION OF RESULTS.

For convenience we shall first discuss the results obtained in the scattering experiment, and then go on to the results of the filtering experiment.

The Scattering Experiment.

Before we can make any deductions from the results of these experiments, we must decide which of the two types of results (those showing constant ionisation ratios with increasing thicknesses of Aluminium inserted between the X-ray tube and scatterer, or those showing a decreasing ratio) are truly representative of properties associated with the phenomena of scattering of radiation by matter.

As already mentioned, the type of result obtained seemed to depend on the apparatus or arrangement of apertures used, and that the most apparent difference in the two sets of apparatus was that those giving a constant ratio only had one 'effective' secondary aperture which defined the scattered beam, and those giving a decreasing ratio had two secondary apertures defining the scattered beam.

In the former case, it is obvious that the cross sectional area and shape of the scattered beam was governed not only by the size of the secondary aperture, but also by the size and shape of the patch of the scatterer which was irradiated by the incident radiation, as shown in A Fig. 62.

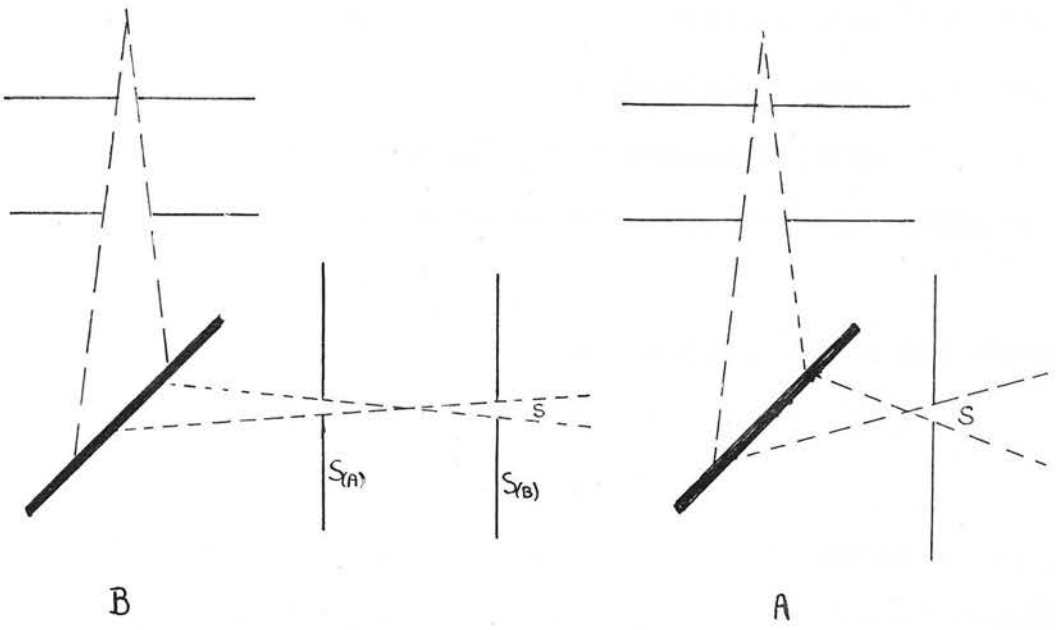


Fig 62

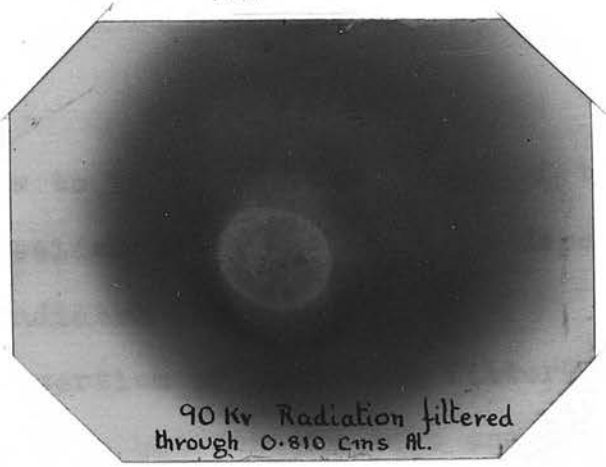
In the other case, however, the cross sectional area and shape of the scattered beam was entirely governed by the sizes and shapes of the two secondary apertures, provided the irradiated patch on the scatterer was large enough, as shown in B, Fig. 62.

This latter arrangement of the apparatus thus seems to be more desirable, as any change in the 'spread' of the focal point of the electrons on the target of the X-ray tube (which may possibly occur when the potential difference across the tube is varied) would lead to a change in the size of the patch of the scatterer which is irradiated by the incident radiation. If the scattered beam is already fully defined by the <u>two</u> secondary apertures, this change in the size of the irradiated patch would not produce any change in the cross sectional area of the scattered beam, and would thus not produce any spurious effects which might be attributed to the actual mechanism of scattering.

On the other hand, with a single secondary aperture the cross sectional area of the scattered beam will vary with changes in the area of the irradiated patch on the scatterer, and the interpretation of the experimental results obtained may prove very confusing.

Any effects produced by varying sizes and shapes of the irradiated patches on the scatterers will be more marked with thick than with thin scatterers.

From these considerations, we may tentatively attempt to explain the difference in the two types of results (constant or decreasing ionisation ratio with increasing thickness of filter inserted between the X-ray tube and the scatterer) by postulating that the decreasing ionisation ratio represents a more correct picture of the variation of the mechanism of scattering with the hardness of the incident radiation, and that this decrease in the ionisation ratio takes place quite independently of the arrangement of the apertures used. But somehow the insertion of an Aluminium filter between the X-ray tube and the scatterer produces a broadening of the incident beam, thereby increasing the area of the irradiated patch on the scatterer, and (in the case where the secondary beam is defined only by a single aperture and the area of the irradiated patch) causing a larger amount of radiation to be scattered into the secondary ionisation chamber, thus increasing the ionisation ratio S/P and masking the postulated true decrease in the ionisation ratio found in cases where the secondary beam is completely defined by two secondary apertures and arranged so as to make the beam independent of the size of the irradiated patch on



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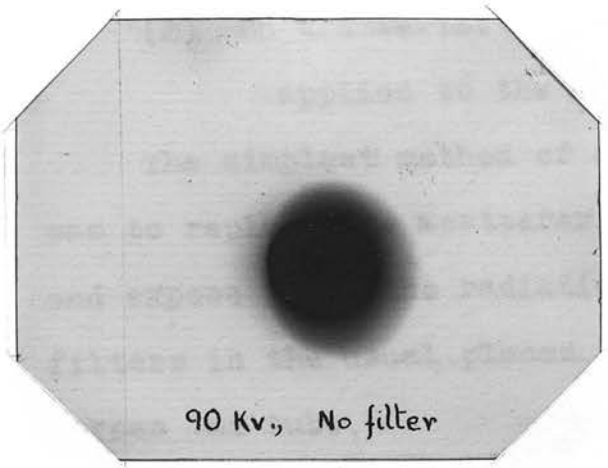
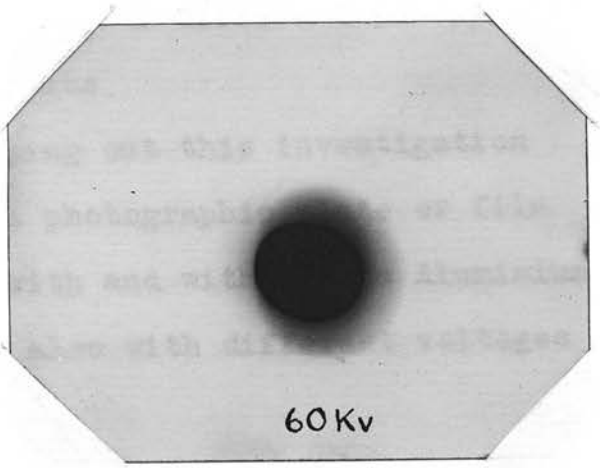
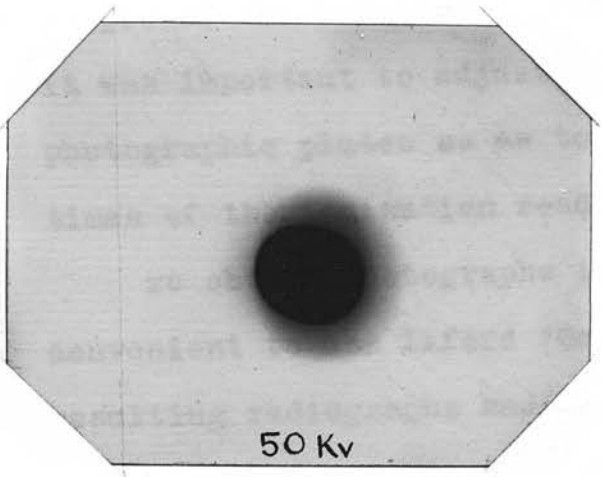
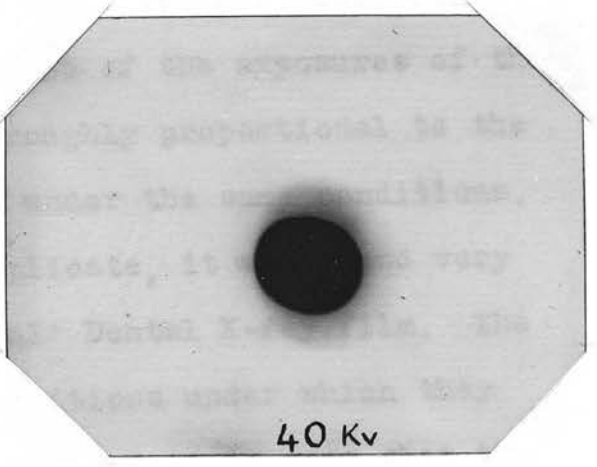








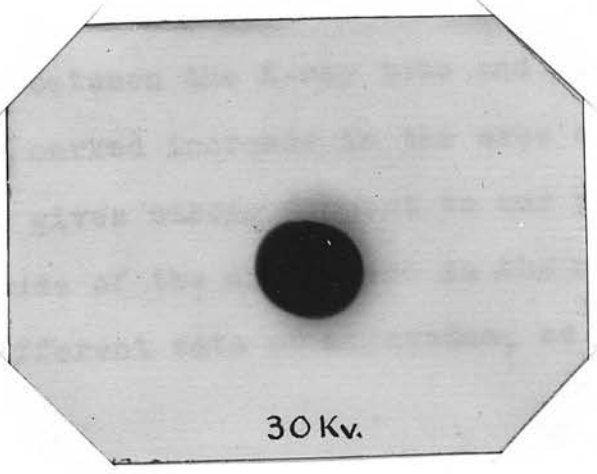


Fig 63.

the scatterer.

With a view to testing the validity of the above explanation, it was decided to investigate the dependence of the size of the irradiated patch on

(1) The insertion of Aluminium filters in the usual position between the tube and the scatterer, and

(2) On the variation produced with different potentials applied to the X-ray tube.

The simplest method of carrying out this investigation was to replace the scatterer by a photographic plate or film and expose it to the radiations with and without the Aluminium filters in the usual places, and also with different voltages across the tube.

In order to get reasonable comparisons of the sizes and shapes of the irradiated patches under various conditions, it was important to adjust the times of the exposures of the photographic plates so as to be roughly proportional to the times of the ionisation readings under the same conditions.

To obtain photographs in duplicate, it was found very convenient to use Ilford 'Oclussal' Dental X-ray film. The resulting radiographs and the conditions under which they were obtained are shown in Fig. 63, and it is seen that the insertion of an Aluminium filter 0·810 cms. in thickness in the usual place between the X-ray tube and the scatterer produces a very marked increase in the area of the irradiated patch, and thus gives strong support to our proposed explanation of the cause of the difference in the results obtained with the two different sets of apparatus, as outlined above.

The radiographs of Fig. 63 also show that when no filter is present, the irradiated patch is of a rather complex nature consisting principally of an intense roughly circular patch, presumably originating from the radiation emitted at the focus of the X-ray tube and passing through the two main primary apertures; and a sort of excentric, somewhat diffuse halo surrounds the central intense patch.

By measuring the dimensions of this halo and projecting lines backwards on a scale drawing of the aperture system used, this halo appears to originate from a roughly elliptic source having a vertical minor axis measuring about 3 to 3·5 cms, and thus presumably corresponding to the whole of the oblique face of the massive copper anode of the X-ray tube in which the tungsten targe is imbedded.

The excentricity of this 'halo' with respect to the central intense patch of focal origin is probably due to a slight convexity of the oblique face of the copper anode, which seems to be a characteristic of many modern X-ray tubes.

In producing the photographs shown in Fig. 63, the correct exposures were made by using the following procedure.

First the film was exposed to 90 Kv., 2 ma. radiation with no filters, and a satisfactory exposure time found by trial and error was 2·0 minutes.

Now, from a typical scattering experiment with the same current flowing through the X-ray tube, the 90 Kv. radiation required 4 minutes to produce an electroscope gold leaf deflection of 15 divisions. But when an

Aluminium filter 0·810 cms. in thickness was inserted between the X-ray tube and the scatterer, the time required for an ionisation corresponding to 15 divisions was found to be 30 minutes, or 7·5 times as long as when no filter was present.

Accordingly, for the radiograph with a 0·810 cms. Aluminium filter in the usual place between the tube and the scatterer, the exposure time was made 7·5 times longer or 15 minutes. In this way we may safely assume that the various radiographs are reasonably representative of the sizes and shapes of the irradiated patch on the scatterer during a typical scattering experiment.

The increase in the size of the irradiated patch on the scatterer when an Aluminium filter is introduced into the incident beam between the tube and the scatterer would thus, at least qualitatively, explain the difference between the two types of results obtained with the different sets of apparatus.

To test the postulated cause of this difference further (as outlined on page 126), the scattering experiment was again repeated with an 11 mm. Paraffin Wax scatterer using apparatus II which was fitted with two secondary apertures, and a 10% drop in the ionisation ratio was found to take place on the insertion of an Aluminium filter 0·810 cms. in thickness between the tube and the scatterer. The experiment was then repeated after the removal of one of the secondary apertures (by sliding the lead plate containing it out of the wooden grooves), leaving in its place an aperture 4·0 cms. in diameter and thus converting the apparatus into one, having only one effective secondary aperture. The other apertures and conditions were unaltered. This experiment gave a drop

in the ionisation ratio of only 1 per cent with the introduction of the same thickness of Aluminium filter in the same place as in the previous case. The two results together with their respective secondary apertures are shown in Fig. 64.

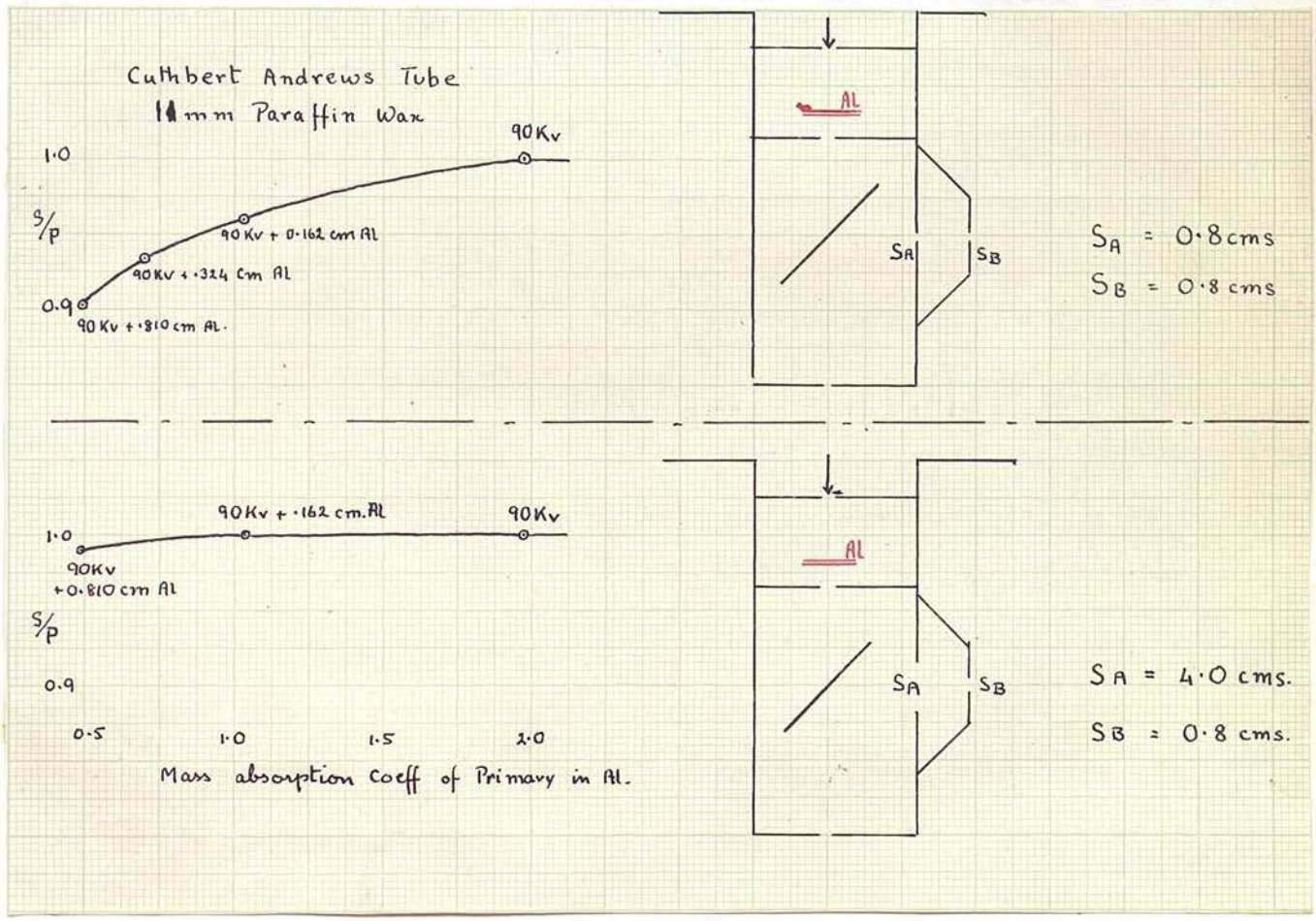


Fig 64

Careful measurements and scale drawings of the aperture systems showed that even with the single secondary aperture, the scattered beam was not wide enough to strike the metal

parts of the electrode system or sides of the ionisation chamber.

The results of the various experiments described in this paper thus show the importance of using apparatus equipped with at least two apertures of such dimensions as to give a scattered beam whose cross sectional area is independent of the variation in size of the patch to define the scattered beam, and seem to show that if this precaution is taken, then, with the exception of Boron scatterers, the ionisation ratio invariably decreases as the incident beam is hardened by filtering through Aluminium. Under these circumstances, it was found that the decrease in the ionisation ratio was independent of the thickness of the scatterer to within about 2 per cent, but did depend on the substance of the scatterer, being greatest for Paraffin Wax scatterers and nil for Boron scatterers.

Aperture conditions which gave a constant ionisation ratio with Paraffin Wax scatterers showed an increasing ionisation ratio with the insertion of Aluminium filters when Boron scatterers were used; thus again confirming a marked difference in the scattering from Boron as compared with scattering from Paraffin Wax.

The writer does not wish to suggest that the constant ionisation ratios observed by some workers when hardening the radiation by filtering the incident beam through Aluminium is due to the arrangement of the apertures or other parts of the apparatus as discussed above rather than to some fundamental phenomena associated with the scattering of certain types of radiations. He merely presents the results of his

own experiments which, with the exception of Boron scatterers, invariably show a decreasing ionisation ratio as the radiation incident on the scatterer is progressively hardened by filtering through Aluminium, except in those cases where a single 'effective' secondary aperture was used and the result could, at least qualitatively, be explained by a broadening of the irradiated patch on the scatterer as outlined above.

We may summarize the results obtained as follows:-

(1) As the potential difference across the X-ray tube is increased from about 20-30 Kv., the ionisation ratio S/P steadily increases up to a certain critical voltage. For higher voltages the ionisation ratio remains constant (to within the experimental error of about one per cent) up to the highest potential difference which could be applied to the tube (except for the Molybdenum Target tube already mentioned).

(2) The value of the critical voltage across the tube, mentioned above, depends on the X-ray tube used, and on the thickness of the scatterer, being considerably lower for thin scatterers than for thick ones.

There is some indication of a slight variation of the critical voltage with the atomic number of the scatterer. The higher the atomic number of the latter, the higher the value of the critical voltage.

The critical voltage appears to be independent of

the sizes of the primary or secondary apertures, provided saturation of the ionic currents in the ionisation chambers is ensured, and the secondary beam is fully defined by two apertures, as already discussed.

(3) When the hardness of the incident radiation is increased by filtering through Aluminium sheets inserted between the tube and the scatterer, the ionisation ratio decreases as thicker filters are used.

For a given X-ray tube, operating under a constant potential difference of 90 Kv. and a current of 2·0 ma., the decrease in the ionisation ratio produced by the insertion of an Aluminium filter 0·810 cms. thick between the X-ray tube and the scatterer was found to depend on the X-ray tube used and to be <u>independent</u> of the primary aperture and the thickness of the scatterer ranging from 19 mm. to 3 mm. of Paraffin Wax.

(4) The above decrease in the ionisation ratio S/P was found to depend on the atomic number of the scatterer. If we assume that the scattering from Paraffin Wax is mainly due to the hydrogen atoms, then the drop in the ionisation ratio produced by the standard conditions given in (3) above apparently decreases as the atomic number of the scatterer is increased up to Boron (atomic number 5), for which the ionisation ratio is constant at least up to this thickness of Aluminium filter.

For Carbon and Aluminium scatterers the ionisation ratio again drops with the insertion of Aluminium filters in the incident beam, but the drop produced under the above standard conditions was only about 3% with a 0·9 cms. carbon scatterer as compared with a drop of 10% in the case of a 1·1 cms. Paraffin Wax scatterer.

This variation of the drop of the ionisation ratio with the atomic number of the scatterer is particularly interesting as it does not seem to be accounted for by either the Quantum or the Classical theories of scattering.

It should, however, be stated that the quantum theory, as developed by Klein-Nishina, does predict a decrease in the electronic scattering coefficient with increase in the frequency or 'hardness' of the incident radiation, and at first sight this prediction seems to be confirmed by the decreasing ionisation ratio S/P when the incident radiation is hardened by filtering through Aluminium as observed in our experiments. But, as already stated, if the scattered radiation experiences a change in wavelength, as required by the above quantum theory, then, since the change in wavelength is independent of the wavelength of the incident radiation, it follows that the scattered radiation will be comparatively much more absorbable in the gas in the ionisation chambers than the primary radiation and would thus give an increasing ratio as the hardness of the incident radiation is increased.

Compton had suggested that the increasing ionisation ratio with increasing hardness of the incident radiation in

an experiment of this type might be completely masked by the opposing effect due to the decreasing scattering coefficient as the hardness of the incident radiation is increased since this effect would produce a decreasing ionisation ratio S/P. In fact, Compton even suggested that results showing regions of constant ionisation ratios S/P may be attributed to the compensating action of the two processes.

It is, however, difficult to see how this type of compensating effect could account for the considerable ranges of absorption coefficients over which the ionisation ratio S/P is found to be constant, and for the sudden change from a constant ionisation ratio to a decreasing ionisation ratio as the voltage across the tube is reduced below the critical voltage already described.

Furthermore, the drop in the ionisation ratio produced by the insertion of Aluminium filters between the X-ray tube and the scatterer does not depend critically on the absorption coefficient of the incident radiation, since in some experiments the drop in the ionisation ratio with the tube operating at 40 Kv. and 90 Kv. was of the same order of magnitude in the two cases when the same thickness of Aluminium filter was inserted in the incident beams (as shown in Fig. 65). The corresponding spectral intensity distributions for the two cases are also shown.

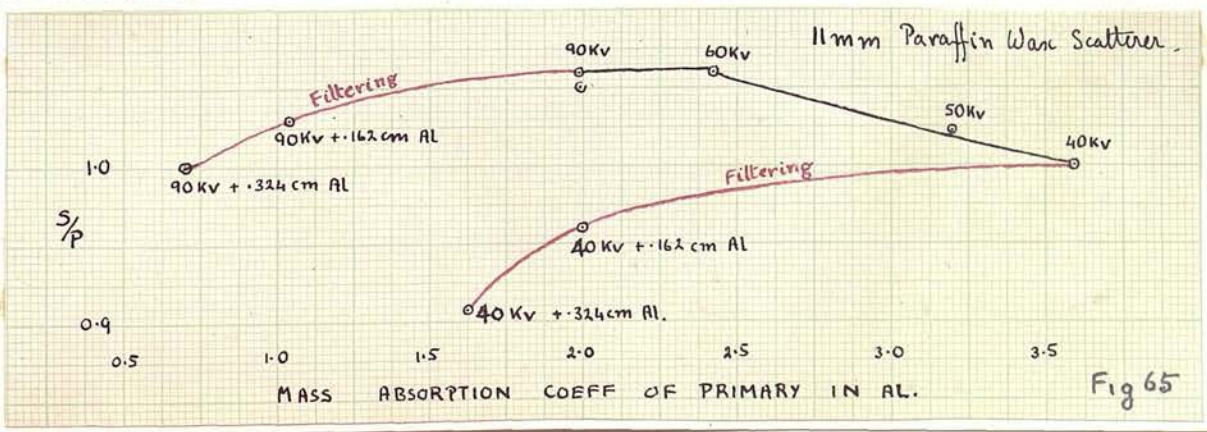


Fig 65

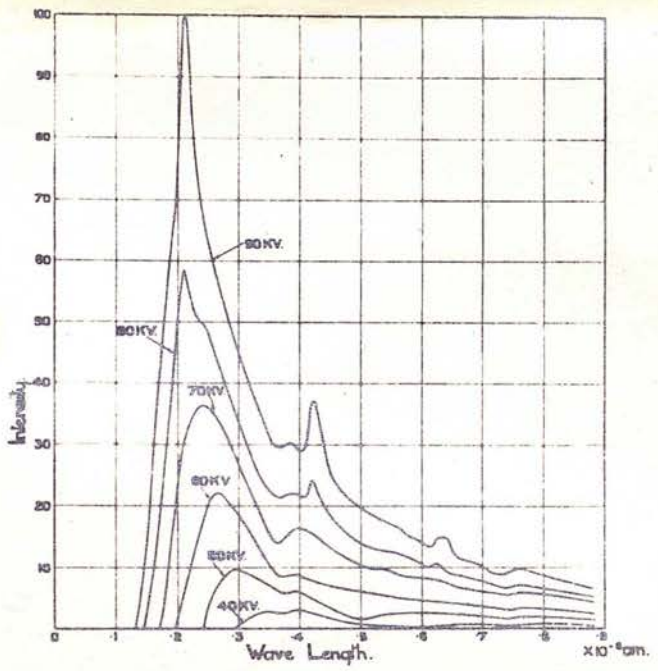


FIG. ■—X-ray spectrum of tungsten at various voltages and const. milliamps; no filter. NaCl crystal (Hull).

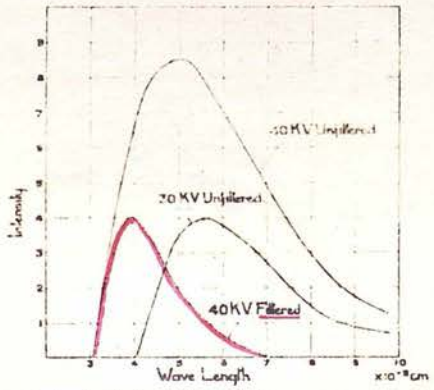


FIG. ■.—X-ray output of Coolidge tube. 40,000 volts (unfiltered and 3 mm. Al. filter) and 30,000 volts (unfiltered).

Fig 65'

These results seem to show that the scattering process is somehow dependent on the method by which the incident heterogeneous radiation is hardened rather than on the actual degree of hardness of the incident radiation. In particular, incident radiation which has been hardened by filtration through Aluminium seems to be scattered differently to the incident radiation hardened by raising the voltage across

the X-ray tube, the average mass absorption coefficients in the two cases being comparable.

It thus appears that radiation which has traversed considerable thicknesses of matter is scattered differently from radiation which has passed through only thin sheets of matter before scattering, although the mass absorption coefficients of the two radiations incident on the scatterer (as measured by the conventional 50% reduction in intensity) are of the same order of magnitude, except in the case of Boron scatterers, in which case there does not seem to be any difference in the process of scattering of either type of radiation.

This fundamentally different behaviour of Boron scatterers cannot possibly be due to any error in the experiment as it has been checked and re-checked very carefully. Furthermore, marked differences in the behaviour of Boron scatterers with radiations of different wavelengths as compared with scatterers of other elements of both lower and higher atomic numbers have been found and commented on by Mertz (22) in U.S.A.

The variation of the electronic scattering coefficient with the wavelength of the incident radiation as reported by S.J.M. Allen also shows a marked difference in the scattering properties of Boron. The decrease in the electronic scattering coefficient with decreasing wavelengths is markedly less with Boron scatterers than with Lithium or Carbon scatterers, as shown in Fig. 66, where S.J.M. Allen's electronic scattering coefficients are shown plotted against the wavelength of the incident radiation.

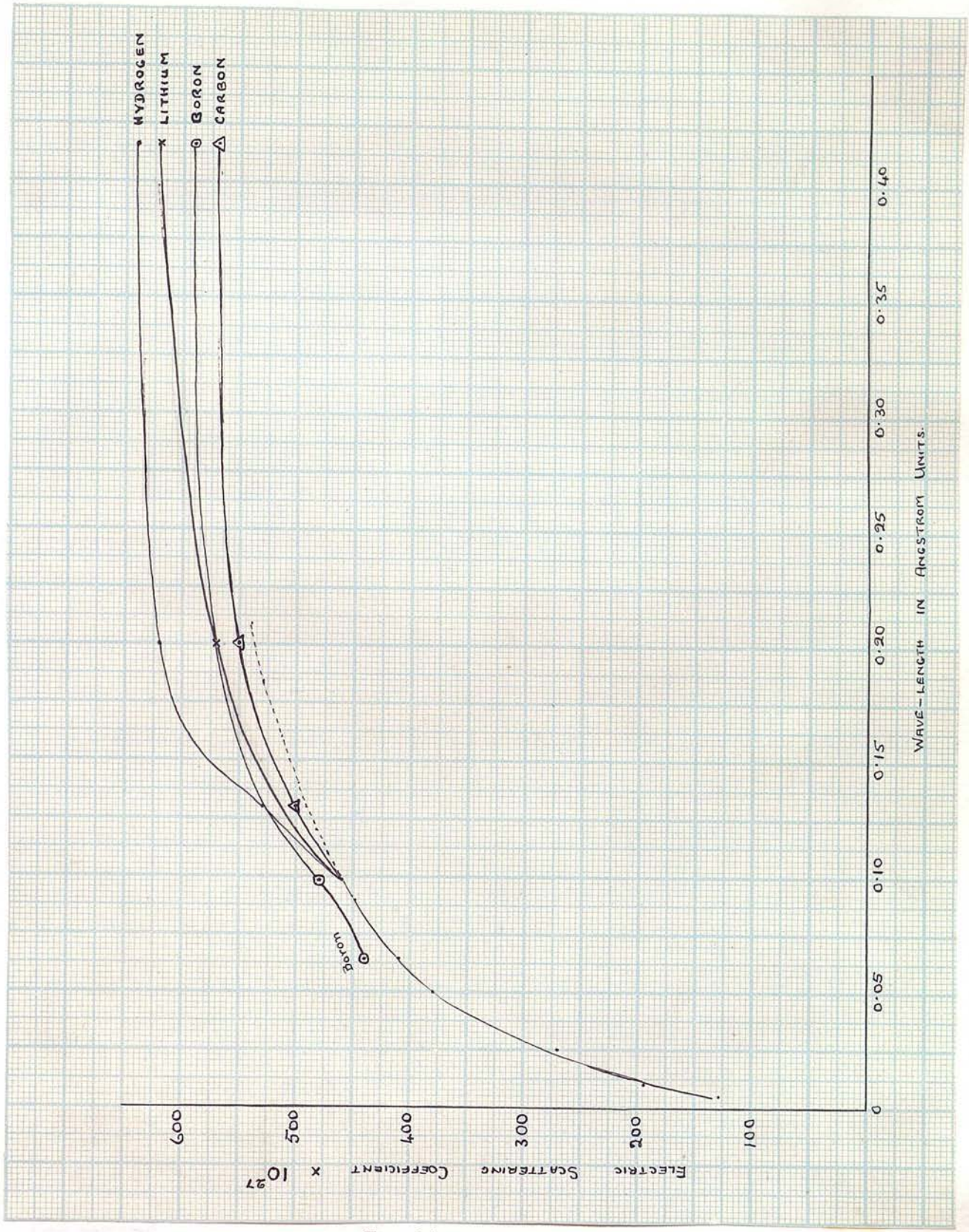


Fig 66.

The results of the above two workers, obtained by quite different methods, seem to indicate that the scattering properties of Boron are, in some respects, fundamentally different from the neighbouring elements of low atomic number

and thus give good support to the fundamentality of the results obtained by the writer where, as already stated, Boron scatterers were found to be unique in that the ionisation ratio S/P was constant for all values of Aluminium filters inserted between the tube and the scatterer up to 0·810 cms (the maximum thickness used).

This result obtained with a Boron scatterer is of profound importance in the interpretation of the results reported earlier in this paper.

In particular, if we return to Fig. 65, where the general radiation emitted by a Cuthbert Andrews Tungsten tube, hardened by two distinct processes, (by raising the potential across the tube, or by filtering the 40 Kv. radiation through Aluminium filters placed between the tube and scatterer) showed an increasing ionisation ratio S/P with the first method and a decreasing ionisation ratio with the second method, we can, at first sight, attempt to explain the difference in the variation of the ionisation ratio with the process of hardening used, by considering polarisation.

Barkla had shown that the percentage polarisation of the general radiation emitted by an X-ray tube decreased as the voltage across the tube was increased, and this would possibly account for the increase in the ionisation ratio S/P in the present experiments as the voltage across the tube was increased.

Also various experiments by many workers seem to show that the degree of polarisation is much greater for wavelengths near the short wave limit of the general radiation than for the longer wavelength components. Consequently, filtering the

radiation would tend to increase the degree of polarisation of the radiation incident on the scatterer, and would thus lead to a decreasing ionisation ratio as the incident radiation is hardened by filtering, as observed in our experiments with Paraffin Wax, Lithium, Beryllium Oxide and Carbon scatterers.

On the other hand, the remarkable constancy of the ionisation ratio when the radiation is hardened by filtering, in the case of Boron scattering, seems to suggest that the phenomena are independent of the polarisation considerations discussed above, and lead to the conclusion that the results reported in this paper indicate the presence of certain phenomena associated with the process of scattering and dependent on both the incident radiation and on the scatterer, which, as yet, cannot be accounted for on either the Quantum or Classical Theories.

Further support of this conclusion is obtained from S.J.M. Allen and T. Cuykendall's experimental investigations of the variation of the electronic scattering coefficient with the wavelengths of the incident radiation. According to classical theory, the electronic scattering coefficient should be a constant, independent of the wavelength of the incident radiation and of the atomic number of the scatterer, except in cases where 'group scattering' occurs, as already described in the Introductory Discussion of this paper.

On the other hand, the Quantum theory requires the electronic scattering coefficient to vary with the wavelength of the incident radiation according to the Klein Nishina formula (shown by the dotted line in Fig. 66).

S.J.M. Allen and T. Cuykendall both find that for wavelengths below about 0·1 A.U. the experimental values of the electronic scattering coefficients of the various elements are in agreement with the Klein-Nishina formula to within the experimental error of about 1 per cent.

For wavelengths above about 0·1 A.U. the experimental values show a marked departure from the Klein-Nishina values in the form of excess scattering. This departure is characterised by a marked point of inflection in the scattering coefficient-wavelength curve at a wavelength of about 0·1 A.U. as shown in Fig. 66.

It is interesting and important to note that the departure from the Klein-Nishina formula is more marked in the case of elements of low atomic number than with those of higher atomic number. Furthermore, the writer found that if the difference between the experimental and Klein-Nishina values of the electronic scattering coefficients $\delta\sigma$, is plotted against the reciprocal of the corresponding wavelength, $1/\lambda$, the resulting curve is a straight line for scatterers of Li, B, C, and Al (and possibly for other elements as well) for considerable ranges of wavelengths.

Typical examples of these curves are shown in Fig. 67; the equations representing them appear to have the form:

$$\delta\sigma = a - \frac{\beta}{\lambda} \qquad (14)$$

Where α and β are constants depending on the atomic number of the scatterer and λ is the wavelength of the incident radiation.

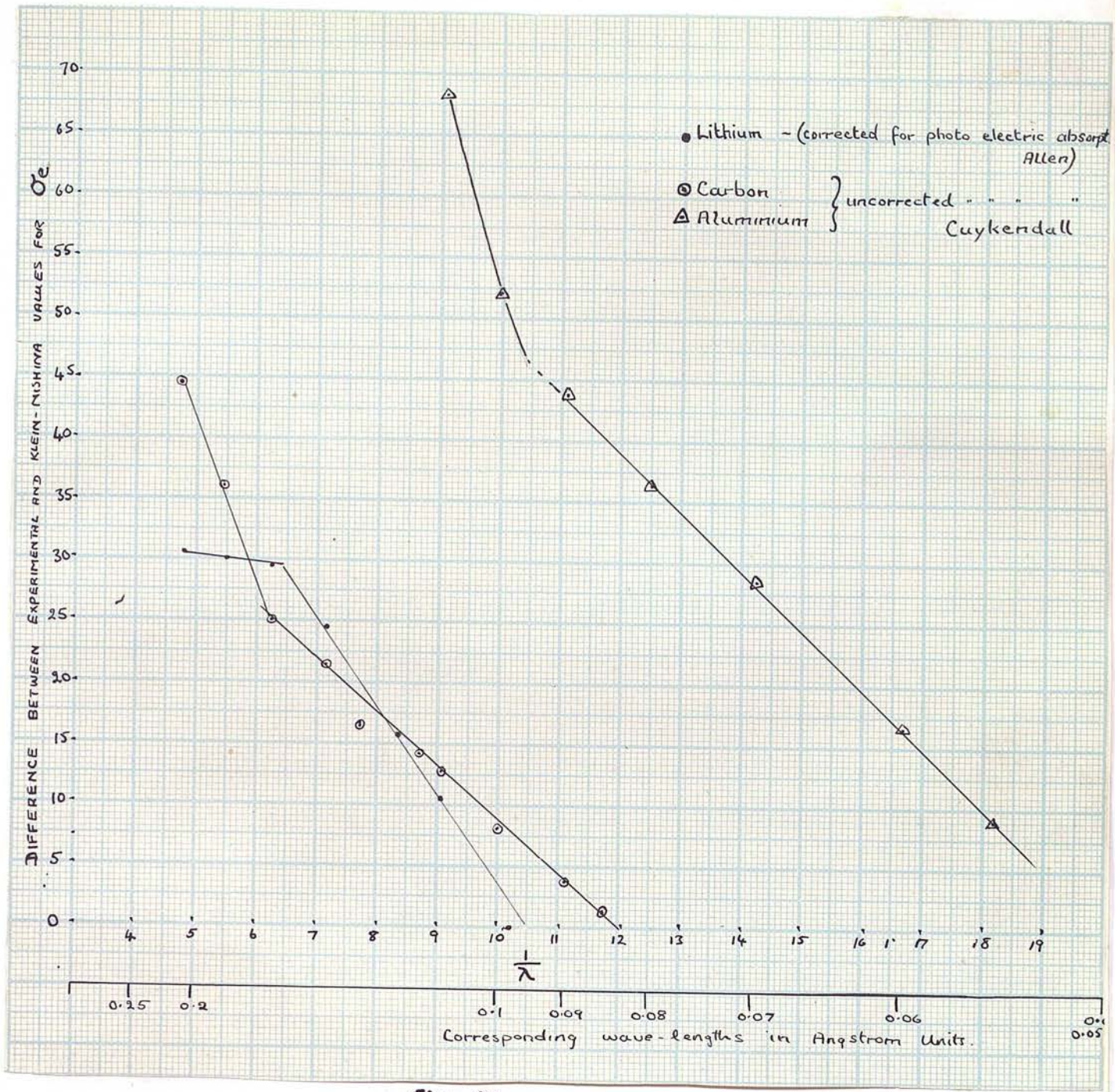


Fig 67.

The deviation of experimental values from those predicted by the Klein-Nishina formula, as given by formula (14), can hardly be accounted for by experimental errors, etc. and again give evidence of the existence of certain phenomena involving the atomic number of the scatterer and the wavelength of the incident radiation, which have not been accounted for by the Quantum and Classical theories of scattering.

DISCUSSION OF THE FILTERING EXPERIMENT.

The results presented in the earlier part of this paper seem to show beyond a doubt that under certain conditions, the difference in the absorbabilities of the scattered and transmitted radiations, as measured in Aluminium, is characterised by the appearance of one or more 'J-discontinuities' or 'kinks'.

The conditions governing the appearance or non-appearance of a discontinuity are as yet uncertain, as they do not seem to depend on experimental parameters usually taken into consideration; but the experimental results seem to indicate that scatterers of low atomic number, Li, BeO, B, and high potential differences across the X-ray tube are important factors, favourable to the appearance of a marked discontinuity.

The writer was unable to confirm the gradual shift of the 'J-discontinuity' or kink towards smaller critical thicknesses of Aluminium filters in the primary and secondary beams as the voltage across the tube was reduced, (reported by Miss Wilson[20] and Reekie[21]). In fact, scatterers of Paraffin Wax, Lithium and Boron gave a shift of the discontinuity in the opposite direction, i.e. to greater thicknesses of filters, in confirmation of Barkla's earlier results.

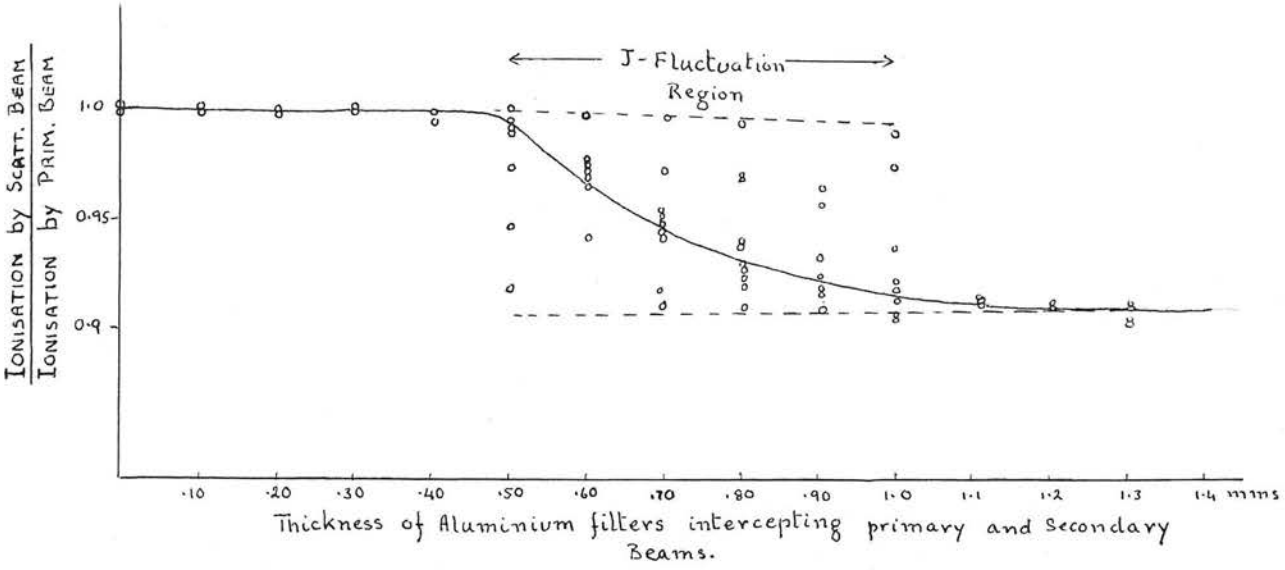
The Beryllium Oxide scatterer, however, did not seem to show any shift of the discontinuity with change of voltage across the tube, but seemed to indicate the existence of a certain optimum voltage of about 90 Kv. for which the kink was most distinct and abrupt.

In confirmation of the findings of Miss Wilson and Reekie, the writer has never observed a discontinuity or 'kink' at voltages less than the critical voltage found in the scattering experiment already described.

As a tentative explanation of this effect, we may suppose that at these low voltages, the degree of polarisation of the general radiation is presumably relatively large and as the short wave components are much more strongly polarised, the scattered radiation will have relatively small intensity in the short wavelength components, and would thus be more absorbable because of this polarisation effect, thereby masking or blurring out the discontinuities which seem to indicate a true transformation of the incident radiation in the process of scattering.

As already described, the 'J-discontinuity' sometimes appeared to be replaced by a discontinuity region over which the values of the intensity ratio S/P fluctuated between two well marked levels corresponding to the levels on either side of a sharp discontinuity. When a large number of determinations of the ratio S/P were made in such a fluctuating region, it was found that with thinner filters in the two beams most of the values were near the upper level. In other words, with thin filters a high value of the ratio S/P was much more probable than a low value, whereas at the other end of the fluctuation region, corresponding to the thicker filters, although the ratio fluctuated between the two levels, a value of the ratio near the lower fluctuation limit was much more probable than a higher value. These results are shown diagrammatically in Fig. 68, where the density of the points give a

measure of the probability of getting a ratio near any particular value.



If we draw a smooth curve through the centre of gravity of these plots, we obtain a roughly exponential curve as already described, and thus seem to be able to form a connecting link between the curves showing discontinuity regions and those showing short initial horizontal sections (or sections having very slight slopes) followed by a roughly exponential curve.

It should be emphasised, however, that the above correlation of the two types of results are only given tentatively and no claim is made that such a correlation would account for different types of curves obtained by experiment.

In conclusion, we may say that the experiments described in this paper definitely show the presence of scattering phenomena closely associated with the atomic number of the scatterer and the wavelength, or degree of hardness of the incident radiation, which so far cannot be accounted for by the Quantum

or Classical theories of scattering, and further work in this field would be very desirable.

REFERENCES.

(1) Coven, Phys. Rev. 38, 1424 (1931).

(2) Hewlett, Phys. Rev. 20, 688 (1922).

(3) Chao, Phys. Rev. 36, 1519 (1930).

(4) Klein and Nishina. Rutherford's Radiations from Radioactive Substances, p.464.

(5) Woo's curves from Compton and Allison's X-rays in Theory and Experiment. p.205.

(6) Woo, Phys. Rev. 26, 427 (1926).

(7) Wentzel, Zeits. f. Physik 1, 43 and 779 (1927).

(8) Waller. Phil. Mag. 4,1228, (1927).

(9) Hartree. Proc. Camb. Phil. Soc. 27, 89 (1928).

(10) Ross, Phys. Rev. 26, 282 (1925).

(11) Ross, Phys. Rev. 25, 235 (1925).

(12) Barkla, Proc. Roy. Soc. 77, 247 (1906).

(13) Compton and Hagenow. Rev. Sc. Inst. 487 (1924).

(14) Cuykendall, Phys. Rev. 50, 105 (1936).

(15) Allen, Phys. Rev. 45, 122 (1934).

(16) Klein and Nishina, Zeits. f. Physik, 52, 853 (1928).

(17) Rodgers, Phys. Rev. 50, 875 (1936).

(18) Kay, Phil. Mag. XVI, 461 (1933).

(19) Bumstead.

(20) Miss Wilson, Ph.D. Thesis, Edin. Univ. 1939.

(21) Reekie, Ph.D. Thesis Edin. Univ. 1939.

(22) Mertz. Phys. Rev. 28, 391, (1926).

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